

The Planetary and Lunar Ephemeris DE 421

W. M. Folkner, J. G. Williams, D. H. Boggs

Abstract

The planetary and lunar ephemeris DE 421 represents the ‘current best estimates’ of the orbits of the Moon and planets. The lunar orbit is currently known to sub-meter accuracy though fitting lunar laser ranging data. The orbits of Venus, Earth, and Mars are known to sub-kilometer accuracy. Because of perturbation of the orbit of Mars by asteroids, frequent updates are needed to maintain the current accuracy into the future decade. Mercury’s orbit is determined to an accuracy of several kilometers by radar ranging. The orbits of Jupiter and Saturn are determined to accuracies of tens of kilometers as a result of spacecraft tracking and modern ground-based astrometry. The orbits of Uranus, Neptune, and Pluto are not as well determined. Reprocessing of historical observations is expected to lead to improvements in their orbits in the next several years.

1. Introduction

The planetary and lunar ephemeris DE 421 is a significant advance over earlier ephemerides. Compared with DE 418, released in July 2007 (Folkner et al. 2007), the current ephemeris includes additional data, especially range and VLBI measurements of Mars spacecraft; range measurements to the ESA Venus Express spacecraft; and use of current best estimates of planetary masses in the integration process. The lunar orbit is more robust due to an expanded set of lunar geophysical solution parameters, seven additional months of laser ranging data, and complete convergence. DE 421 has been integrated over the time period 1900 to 2050. A longer integration has been deferred until some improvements in the dynamical models have been implemented.

While the lunar orbit in DE 421 is close to that in DE 418, it is a major improvement over the widely distributed DE 405 (Standish 1998). For DE 405 the lunar orbit was not fit in a way consistent with the other planets. Continuing the process used to develop DE 418, DE 421 is a combined fit of lunar laser ranging (LLR) and planetary measurements. The DE 421 model is more complete than for DE 418 and has been fully converged, so it is recommended for use by lunar missions.

Also, DE 405 was created in 1995 before the Mars Pathfinder mission in 1997, so the Earth and Mars orbits were largely dependent on range measurements to the Viking landers from 1976 to 1982 augmented by radar range observations with an accuracy of about 1 km. The error in the Earth and Mars orbits in DE 405, is now known to be about 2 km, which was good accuracy in 1997 but much worse than the current sub-kilometer accuracy.

Because of perturbations of the orbit of Mars by asteroids, frequent updates are needed to maintain the current ephemeris accuracy into the future decade. The orbits of Earth and Mars are continually improved through measurements of spacecraft in orbit about Mars. DE 421 incorporates range data through the end of 2007. VLBI observations of Mars spacecraft were resumed in January 2006 to improve the Mars orbit accuracy for the MSL project. VLBI data

through December 2007 have been included in the DE 421 estimate. The Earth and Mars orbit accuracies are expected to be better than 300 m through 2008.

The Venus orbit accuracy has been significantly improved by inclusion of range measurement to the Venus Express spacecraft. Combined with VLBI measurements of Magellan, and one VLBI observation of Venus Express, the Venus orbit accuracy is now about 200 meters.

The orbit of Mercury is currently determined by radar range observations. Since the last radar range point is in 1999, the estimated Mercury orbit has not changed significantly for the past decade. The current orbit accuracy is a few kilometers. Measurements of the Messenger spacecraft are expected to lead to a significant improvement over the next several years.

The orbits of Jupiter and Saturn are determined to accuracies of tens of kilometers using spacecraft tracking and modern ground-based astrometry. The orbit of Saturn is more accurate than that of Jupiter since the Cassini tracking data are more complete and more accurate than previous spacecraft tracking at Jupiter. The orbits of Uranus, Neptune, and Pluto are not as well determined. Reprocessing of historical observations is expected to lead to improvements in their orbits in the next several years.

Below we briefly summarize the dynamical modeling assumptions used in the development of DE 421 and the measurements used in its estimation.

2. Planetary Ephemeris Dynamical Modeling

The time coordinate for DE 421 is consistent with the metric used for integration. The coordinate time has been scaled such that at the location of the Earth the coordinate time has no rate relative to atomic time. In a resolution adopted by the International Astronomical Union in 2006 (GA26.3), the time scale TDB (Temps Dynamique Barycentrique, Barycentric Dynamical Time) was defined to be consistent with the JPL ephemeris time. The conversion from atomic time to coordinate time has been done using the formulation of Fairhead and Bretagnon (1990), updated by Fukushima and Irwin (1999) which is consistent, for planetary navigation accuracies, with the simpler approximation given in Moyer (2000).

The axes of the ephemeris are oriented with respect to the International Celestial Reference Frame (ICRF). The Mars spacecraft VLBI measurements serve to tie the ephemeris to the ICRF with accuracy better than 1 milli-ascsecond (1 mas \approx 5 nanoradian) for the planets with accurate ranges.

For DE 421 the positions of the moon and planets were integrated using a n-body parameterized post-Newtonian metric (Will and Nordtvedt, 1972; Will 1981; Moyer 2000). The PPN parameters γ and β have been set to 1, their values in general relativity. Extended body effects for the Earth-Moon system are described in a companion memo (Williams et al. 2008). The oblateness of the Sun has been modeled with J_2 set to 2.0×10^{-7} . Along with the Earth/Moon mass ratio, the mass parameter GM for the Sun, which is by convention a fixed value in units of AU³/day², was estimated in units of km³/s² by solving for the AU in km in the development of DE 421. The mass parameter of the Earth-Moon system was held fixed to a previous LLR-only estimate. The mass parameters for the other planets (planetary systems for planets with natural satellites) were taken from published values derived from spacecraft tracking data. The mass parameters used for the Sun and planets are given in Table 1.

Table1: Mass parameters of planetary bodies/systems used in DE 421

| Body/System | GM (km ³ /s ²) | GM _{sun} /GM _{planet} | Reference |
|-------------|---------------------------------------|---|------------------------|
| Mercury | 22032.090000 | 6023597.400017 | Anderson et al [1987] |
| Venus | 324858.592000 | 408523.718655 | Konopliv et al. [1999] |
| Earth | 398600.436233 | 332946.048166 | See text |
| Mars | 42828.375214 | 3098703.590267 | Konopliv et al. [2006] |
| Jupiter | 126712764.800000 | 1047.348625 | Jacobson [2005] |
| Saturn | 37940585.200000 | 3497.901768 | Jacobson et al. [2006] |
| Uranus | 5794548.600000 | 22902.981613 | Jacobson et al. [1992] |
| Neptune | 6836535.000000 | 19412.237346 | Jacobson et al. [1991] |
| Pluto | 977.000000 | 135836683.767599 | Jacobson et al. [2007] |
| Sun | 132712440040.944000 | 1 | Estimated |
| Moon | 4902.800076 | 27068703.185436 | See text |
| Earth-Moon | 403503.236310 | 328900.559150 | LLR fit |

The orbit of the Sun was not integrated in the same way as the other planets. Instead, the position and velocity of the Sun were derived at each integration time step to keep the solar system barycenter (Estabrook 1971) at the center of the coordinate system.

The Newtonian effects of 67 ‘major’ asteroids and 276 ‘minor’ asteroids that introduce the largest perturbations on the orbit of Mars have been included in the integration of the planetary orbits in an iterative manner. The orbits of Ceres, Pallas, and Vesta were integrated simultaneously, including mutual interactions, holding the orbits of the Sun and planets to those in DE 405. The orbits for the other asteroids were integrated individually under the gravitational forces from the Sun, planets, and Ceres, Pallas and Vesta, whose orbits were held fixed. The mass parameters of Ceres, Pallas, and Vesta, and eight other asteroids were then estimated in fitting the DE 421 data. The mass parameters of the remaining 56 ‘major’ asteroids were held at assumed nominal values. The mass parameters of the major asteroids are given in Appendix A. The minor asteroids were divided into three taxonomic types (classes). The volume of each minor asteroid was based on a nominal radius and the density of each of the three types of asteroids was estimated. The estimated densities and the radii assumed for the minor asteroids are given in Appendix A.

The selection of which asteroid mass parameters to estimate was based on an empirical process to see which set produced a reasonably accurate prediction of the Earth-Mars range over one year. For example, Figure 1 shows Mars Odyssey range residuals relative to DE 418, which was fit to range data through end of 2006. DE 418 is seen to predict range to Mars one year into the future with an accuracy of about 15 m. Similarly DE 421 is expected to predict the Earth-Mars range to about 15 m through end of 2008. (The error in the plane-of-sky position of Mars relative to Earth through end of 2008 is about 300 m.) This is relevant for navigation of the Phoenix spacecraft with arrival at Mars in May 2008. The estimated mass parameters of the selected asteroids and estimated asteroid class densities are not necessarily the best possible values for other purposes.

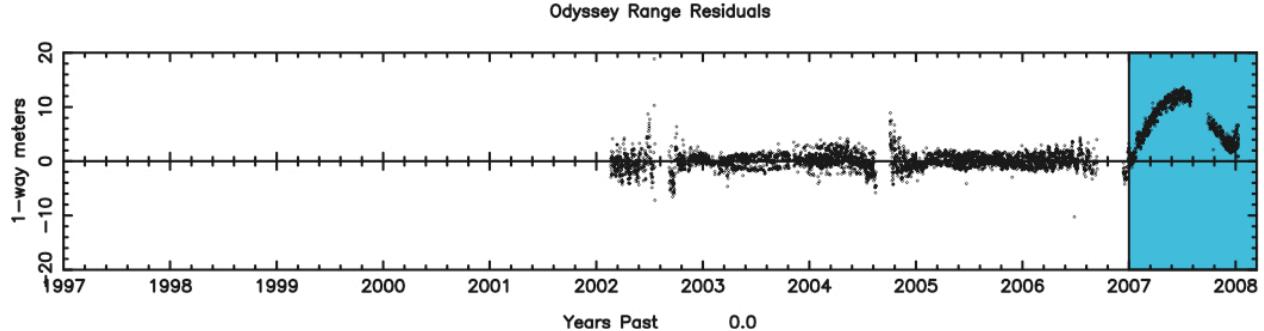


Figure 1: Mars Odyssey spacecraft range measurement residuals to planetary ephemeris DE 418. DE 418 was fit to range measurements through end of 2006. The range residuals for data in 2007 (in shaded area) are less than 15 m and indicate the ephemeris prediction accuracy.

3. Measurement Set

Rather than try to fit all available planetary observations, the data used for DE 421 were preferentially selected for the best accuracy and (for angular data) accuracy of ties to the ICRF. The measurements are summarized in Table 2 and Table 3. Plots of the residuals for all data are included in Appendix B. The data for each planet contain primary data that have the most strength for determining the orbit, and, for some planets, secondary data that are included in the fit at their nominal weight but do not affect the orbit significantly.

Lunar laser ranging, spacecraft ranging, and radar ranging are all very accurate and independent of reference frame. VLBI observations of spacecraft in orbit about Venus, Mars, Jupiter, and Saturn relative to extragalactic radio sources defining the ICRF tie the planetary ephemeris to the ICRF.

Analysis of spacecraft range and Doppler observations taken as spacecraft fly by planets can give right ascension and declination with accuracy somewhat less than the VLBI observations. These right ascension and declination determinations are important in refining the orbits of Jupiter and Saturn. The accuracy of spacecraft plane-of-sky determinations is very much a function of time. The earliest planetary encounters relied on S-band (2 GHz) radio systems with range and Doppler measurement accuracy very sensitive to electrons in the solar plasma. Later spacecraft observations (e.g. after 1990) used X-band (8 GHz) radio systems that were much less affected by solar plasma. Early spacecraft encounter data were processed with reference frame models not well linked to the current ICRF, and often saw discrepancies between range and Doppler data. Data from most encounters have since been re-processed with modern reference frame models so the determined plane-of-sky positions are consistent with the ICRF. For each encounter a single vector for range, right ascension, and declination was generated. For Cassini, a vector was generated for each orbit about Saturn.

Astrometric observations of the planets in the past have suffered from difficulty in establishing an accurate celestial reference frame. Since the release of the Hipparcos star catalog, and the development of techniques for using CCD instruments, astrometric accuracies are approaching spacecraft VLBI accuracies. However these observations only cover a fraction of the orbital periods of the outer planets. Since the orbits of Jupiter and Saturn are well determined from spacecraft data, the limited time span of modern data mainly affects the orbital uncertainties of Uranus, Neptune, and Pluto. The Pluto data set was discussed in detail in relation to the ephemeris DE 418 (Folkner et al. 2007). For the orbit of Pluto in DE421, we followed the

same approach used for DE 418, with two more months of observations. For Uranus and Neptune the assessment of older data sets is not as complete as for Pluto so relatively few data have been included. These orbits are reasonably accurate for the current times due to modern astrometry and knowledge from the Voyager encounters. The Uranus and Neptune data sets will be expanded in a future ephemeris.

Most of the data used are not published but communicated to the authors electronically. Most data are available at the web site <http://iau-comm4.jpl.nasa.gov/plan-eph-data/> or by request from the authors. Lunar laser ranging data are posted by the International Laser Ranging Service (Pearlman et al 2002; <http://ilrs.gsfc.nasa.gov/>). A Mariner 10 range to Mercury was reported by Anderson et al. (1987). A Goldstone radar range to Mercury is from Jurgens et al. (1998). Radar ranges to Mercury and Venus from Eupatoria are from Kotelnikov et al (1983; <http://www.ipa.nw.ru/PAGE/DEPFUND/LEA/ENG/rrr.html>). Astrometry data from the US Naval Observatory are from Stone et al. (2003; <http://www.nofs.navy.mil/data/plansat.html>). Older observations from Pluto are taken from the literature (see references: Barbieri, Cohen, Jenson, Gemmo, Klemola, Rapaport, Rylkov, Sharaf, Zappala). Other data were via private communications.

4. Availability

The DE421 ephemeris may be downloaded in an ascii version from

<ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421> .

The complete set of input parameters for the solar system integration is part of the file. The SPICE kernal version of DE421 is available at

<ftp://ssd.jpl.nasa.gov/pub/eph/planets/bsp> .

Table 2: Summary of data used to estimate orbits of the Moon, inner planets and Jupiter. Data with relatively little contribution to the estimates orbits are indicated in italics.

| Planet | Meas | Type | Obs | Span | #meas |
|---------|------------|---------|----------------|-----------|--------|
| | | range | | | |
| Moon | LLR | range | McDonald 2.7m | 1970–1985 | 3451 |
| | | | MLRS/saddle | 1984–1988 | 275 |
| | | | MLRS/MtFowlkes | 1988–2007 | 2746 |
| | | | Haleakala | 1984–1990 | 694 |
| | | | CERGA | 1984–2005 | 9177 |
| | | | Matera | 2004 | 11 |
| | | | Apache Pt | 2006–2007 | 247 |
| Mercury | Radar | range | Arecibo | 1967–1982 | 242 |
| | | | Goldstone | 1972–1997 | 283 |
| | | | Haystack | 1966–1971 | 217 |
| | | | Eupatoria | 1980–1995 | 75 |
| | Radar | closure | Goldstone | 1989–1997 | 40 |
| | Spacecraft | range | Mariner 10 | 1974–1975 | 2 |
| | | | | | |
| Venus | Spacecraft | range | VEX | 2006–2007 | 14304 |
| | | | VEX | 2007 | 1 |
| | Spacecraft | VLBI | MGN | 1990–1994 | 18 |
| | | | Cassini | 1998–1999 | 2 |
| | Spacecraft | 3-D | Arecibo | 1967–1970 | 227 |
| | | | Goldstone | 1970–1990 | 512 |
| | Radar | range | Haystack | 1966–1971 | 229 |
| | | | Millstone | 1964–1967 | 101 |
| | | | Eupatoria | 1962–1995 | 1134 |
| | | | | | |
| | | | | | |
| Mars | Spacecraft | range | Viking L1 | 1976–1982 | 1178 |
| | | | Viking L2 | 1976–1977 | 80 |
| | | | Pathfinder | 1997 | 90 |
| | | | MGS | 1999–2006 | 164781 |
| | | | Odyssey | 2002–2007 | 251999 |
| | | | MEX | 2005–2007 | 63133 |
| | | | MRO | 2006–2007 | 7972 |
| | Spacecraft | VLBI | MGS | 2001–2003 | 14 |
| | | | ODY | 2002–2007 | 66 |
| | | | MRO | 2006–2007 | 14 |
| Jupiter | Spacecraft | 3-D | Pioneer 10 | 1973 | 1 |
| | | | Pioneer 11 | 1974 | 1 |
| | | | Voyager 1 | 1979 | 1 |
| | | | Voyager 2 | 1979 | 1 |
| | | | Ulysses | 1992 | 1 |
| | | | Cassini | 2000 | 1 |
| | CCD | ra/dec | USNOFS | 1998–2007 | 2533 |
| | Spacecraft | VLBI | Galileo | 1996–1997 | 24 |
| | | Transit | Washington | 1914–1994 | 2053 |
| | | | Herstmonceux | 1958–1982 | 468 |
| | | | La Palma | 1992–1997 | 658 |
| | | | Tokyo | 1986–1988 | 98 |
| | | | El Leoncito | 1998 | 11 |

Table 3: Summary of data used to estimate orbits of Saturn, Uranus, Neptune, and Pluto. Data with relatively little contribution to the estimates orbits are indicated in italics.

| Planet | Meas | Type | Obs | Span | #meas |
|---------|----------------|--------|---------------------|------------------|-------------|
| Saturn | Spacecraft | 3-D | Pioneer 11 | 1979 | 1 |
| | | | Voyager 1 | 1980 | 1 |
| | | | Voyager 2 | 1981 | 1 |
| | | | Cassini | 2004–2006 | 31 |
| | CCD | ra/dec | USNOFS | 1998–2007 | 3153 |
| | | | TMO | 2002–2005 | 778 |
| | <i>Transit</i> | ra/dec | <i>Bordeaux</i> | <i>1987–1993</i> | <i>119</i> |
| | | | <i>Washington</i> | <i>1913–1982</i> | <i>1422</i> |
| | | | <i>Herstmonceux</i> | <i>1958–1982</i> | <i>405</i> |
| | | | <i>La Palma</i> | <i>1992–1997</i> | <i>730</i> |
| | | | <i>Tokyo</i> | <i>1986–1988</i> | <i>62</i> |
| | | | <i>El Leoncito</i> | <i>1998</i> | <i>18</i> |
| Uranus | Spacecraft | 3-D | Voyager 2 | 1986 | 1 |
| | | | USNOFS | 1998–2007 | 1612 |
| | | | TMO | 1998–2007 | 347 |
| | <i>Transit</i> | ra/dec | <i>Bordeaux</i> | <i>1985–1993</i> | <i>165</i> |
| | | | <i>Washington</i> | <i>1914–1993</i> | <i>2043</i> |
| | | | <i>Herstmonceux</i> | <i>1957–1981</i> | <i>353</i> |
| | | | <i>La Palma</i> | <i>1984–1997</i> | <i>1030</i> |
| | | | <i>Tokyo</i> | <i>1986–1988</i> | <i>44</i> |
| | | | <i>El Leoncito</i> | <i>1997–1998</i> | <i>8</i> |
| | | | | | |
| Neptune | Spacecraft | 3-D | Voyager 2 | 1989 | 1 |
| | | | USNOFS | 1998–2007 | 1588 |
| | | | TMO | 2001–2007 | 267 |
| | <i>Transit</i> | ra/dec | <i>Bordeaux</i> | <i>1985–1993</i> | <i>348</i> |
| | | | <i>Washington</i> | <i>1913–1993</i> | <i>1838</i> |
| | | | <i>Herstmonceux</i> | <i>1958–1981</i> | <i>316</i> |
| | | | <i>La Palma</i> | <i>1984–1998</i> | <i>1106</i> |
| | | | <i>Tokyo</i> | <i>1986–1988</i> | <i>59</i> |
| | | | <i>El Leoncito</i> | <i>1998–1999</i> | <i>11</i> |
| | | | | | |
| Pluto | CCD | ra/dec | USNOFS | 1998–2007 | 852 |
| | | | TMO | 2001–2007 | 118 |
| | <i>Photo</i> | ra/dec | misc | 1914–1958 | 42 |
| | | | Palomar | 1963–1965 | 8 |
| | | | Pulkovo | 1930–1992 | 53 |
| | | | Bord/Valin | 1995–2001 | 97 |
| | | | Asiago | 1969–1989 | 193 |
| | | | Copenhagen | 1975–1978 | 15 |
| | | | Lick | 1980–1985 | 11 |
| | | | Torino | 1973–1982 | 37 |
| | | | <i>La Palma</i> | <i>1989–1998</i> | <i>380</i> |
| | | | <i>El Leoncito</i> | <i>1999</i> | <i>33</i> |

Acknowledgements

The planetary ephemeris accuracy is limited by the accuracy of measurements to which it is fit. The present ephemeris improvements are due to contributed data from many people, including Jim Border for the spacecraft VLBI measurements, Don Han for files used to reduce some of the VLBI measurements, Alex Konopliv for reduced NASA Mars spacecraft ranging measurements, Hugh Harris and Alice Monet at the US Naval Observatory in Flagstaff for observations of the outer planets, Trevor Morely and staff at ESOC for Venus Express and Mars Express range measurements, Bob Jacobson for reduction of Voyager, Pioneer, and Cassini spacecraft tracking data, and Bill Owen for observations of the outer planets from Table Mountain Observatory. Modern lunar laser range quality and quantity are the products of the personnel of the McDonald Observatory in Texas, Apache Point Observatory in New Mexico, Observatoire de la Côte d'Azur in France, and Haleakala Observatory in Hawaii. This work is also greatly dependent on the work of M. Standish, who advised us on aspects of the ephemeris development.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

- Anderson, J. D., Colombo, G., Esposito, P. B., Lau, E. L., Trager, G. B., The mass, gravity field, and ephemeris of Mercury, *Icarus*, 71, 337-349, 1987.
- Barbieri, C., Capaccioli, M., Ganz, R., Pinto, G., Accurate positions of the planet Pluto in the years 1969-1970, *Astron. J.*, 77, 521-522, 1972.
- Barbieri, C., Capaccioli, M., Pinto, G., Accurate positions of the planet Pluto in the years 1971-1974, *Astron. J.*, 80, 412-414, 1975.
- Barbieri, C., Pinocchio, L., Capacciloi, M., Pinto, G., Schoenmaker, A. A., Accurate positions of the planet Pluto from 1974 to 1978, *Astron. J.*, 84, 1890-1893, 1979.
- Barbieri, C., Benacchio, L., Capacciloi, M., Gemmo, A. G., Accurate positions of the planet Pluto from 1979 to 1987", *Astron. J.*, 96, 396-399, 1988.
- Cohen, C. J., Hubbard, E. C., Oesterwinter, C., New orbit for Pluto and analysis of differential corrections, *Astron. J.*, 8, 973-988, 1967.
- Estabrook, F. B., Derivation of relativistic Lagrangian for n-body equations containing relativity parameters b and g, JPL memo (internal document), 1971.
- Fairhead, L., Bretagnon, P., An analytical formula for the time transformation TB-TT, *Astron. Astrophys.*, 229, 240-247, 1990.
- Gemmo, A. G., Barbieri, C., Astrometry of Pluto from 1969 to 1989, *Icarus* 108, 174-179, 1994.
- Folkner, W. M., Standish, E. M., Williams, J. G., Boggs, D., H., Planetary and lunar ephemeris DE418, JPL Memorandum 343R-07-005, 2007.
- Fukushima, T. and Irwin A. A., A numerical time ephemeris of the Earth, *Astronomy and Astrophysics*, 348, 642- 652, 1999.

- Jacobson, R. A., Jovian satellite ephemeris JUP230, private communication, 2005.
- Jacobson, R. A., The orbits of the satellites of Pluto PLU017, private communication, 2007.
- Jacobson, R. A., Riedel, J. E., Taylor, A. H., The orbits of Triton and Nereid from spacecraft and Earth-based observations, *Astron. Astrophys.*, 247, 565-575, 1991.
- Jacobson, R. A., Campbell, J. K., Taylor, A. H., Synnott, S. P., The masses of Uranus and its major satellites from Voyager tracking data and Earth-based Uranus satellite data, *Astron. J.*, 103, 2068-2078, 1992.
- Jacobson, R. A., Antreasian, P. G., Bordi, J. J., Criddle, K. E., Ionasescu, R., Jones, J. B., Mackenzie, R. A., Pelletier, F. J., Owen, W. M. jr., Roth, D. C., Stauch, J. R., The gravity field of the Saturnian system from satellite observations and spacecraft tracking data, *Astron. J.*, 132, 2520-2526, 2006.
- Jensen, K. S., Accurate astrometric positions of Pluto, 1975-1978, *Astron. Astrophys. Suppl.*, 36, 395-398, 1979.
- Jurgen, R. F., Rojas, F., Slade, M. A., Standish, E. M., Chandler, J. F., Mercury radar ranging data from 1987 to 1997, *Astron. J.*, **116**, 486-488, 1998.
- Klemola, A. R., Harlan, E. A., Astrometric observations of the outer planets and minor planets: 1980-1982, *Astron. J.*, 87, 1242-1243, 1982.
- Klemola, A. R., Harlan, E. A., Astrometric observations of the outer planets and minor planets: 1982-1983, *Astron. J.*, 89, 879-881, 1984.
- Klemola, A. R., Harlan, E. A., Astrometric observations of the outer planets and minor planets: 1984-1985, *Astron. J.*, 92, 195-198, 1986.
- Konopliv, A. S., Banerdt, W. B., Sjogren, W. L., Venus gravity: 180th degree and order model, *Icarus*, 139, 3-18, 1999.
- Konopliv, A. S., Yoder, C. F., Standish, E. M., Yuan, D., Sjogren, W. L., A global solution for the Mars static and seasonal gravity, Mars orientation, Phobos and Deimos masses, and Mars ephemeris, *Icarus*, 182, 23-50, 2006.
- Kotelnikov V. A., Alexandrov Y. N., Andreev R. A., Vyshlov A. S., Dubrovin V. M., Zajtsev A. L., Ignatov S. P., Kaevitser V. I., Kozlov A. N., Krymov A. A., Molotov E. P., Petrov G. M., Rzhiga O. N., Tagaevskij A. T., Khasyanov A. F., Shakhovskoj A. M., Shchetinnikov S. A., Radar Observations of Planets, *Astronomicheskii Zhurnal*, vol. 60, N 3, 1983.
- Moyer, T. D., Formulation for observed and computed values of Deep Space Network data types for navigation, Monograph 2, Deep Space Communications and Navigation Series, Jet Propulsion Laboratory/California Institute of Technology, 2000.
- Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., The International Laser Ranging Service, Advances in Space Research, Vol. 30, No. 2, pp. 135-143, July 2002, DOI:10.1016/S0273-1177(02)00277-6.
- Rapaport, M., Teixeira, R., Le Campion, J. F., Ducourant, C., Camargo, J. I. B., Benevides-Soares, P., Astrometry of Pluto and Saturn with the CCD meridian instruments of Bordeaux and Valinhos, *Astron. Astrophys.*, 383, 1054-1061, 2002.

Rylkov, V. P., Vityazev, V. V., Dementieva, A. A., Pluto: an analysis of photographic positions obtained with the Pulkovo normal astrograph in 1930-1992, Astronomical and Astrophysical Transactions, vol. 6, pp. 251-281, 1995.

Sharaf. Sh. G., Budnikova. N. A., Theory of the motion of the planet Pluto, Trans. Inst. Theoretical Astronomy, 10, 1-173, 1964 (NASA Technical Translation F-491, 1969).

Standish, E. M., JPL Planetary and lunar ephemeris DE405/LE405, JPL Interoffice Memorandum 312.F-98-04, 1998.

Stone, R. C., Monet, D. G., Monet A. K. B., Harris, F. H., Ables, H. D., Dahn, C. C., Canzian, B., Guetter, H. H., Harris, H. C., Henden, A. A., Levine, S. E., Luginbuhl, C. B., Munn, J. A., Pier, J. R., Vrba. F. J., Walker, R. L., Upgrades to the Flagstaff astrometric scanning transit telescope: a fully automated telescope for astrometry, Astron. J., 126, 2060-2080, 2003.

Will, C. M. and Nordtvedt, K., Conservation laws and preferred frames in relativistic gravity. I. Preferred-frame theories and an extended PPN formalism, Astrophys. J., 177, 757-774, 1972.

Will, C. M., Theory and Experiment in Gravitational Physics, Cambridge University Press, 1981.

Williams, J. G., Boggs, D. H., Folkner, W. M., DE421 Lunar Orbit, Physical Librations, and Surface Coordinates, JPL Interoffice Memorandum 335-JW,DB,WF-20080314-001, March 14, 2008.

Zappala, V., de Sanctis, G., Ferreri, W., Astrometric observations of Pluto from 1973 to 1979, Astron. Astrophys. Suppl., 41, 29-31, 1980.

Zappala, V., de Sanctis, G., Ferreri, W., Astrometric positions of Pluto from 1980 to 1982, Astron. Astrophys. Suppl., 51, 385-387, 1983.

Appendix A: Asteroid Parameters

Table A1: Parameters of ‘major’ asteroids: type; radius r in km; mass parameter GM in km^3/s^2 ; density ρ in gm/cm^3 .

| ID | Name | r | Type | GM | ρ | ID | Name | r | Type | GM | ρ |
|----|------------|-------|------|--------|--------|-----|------------|-------|------|-------|--------|
| 1 | Ceres | 474.0 | G | 62.178 | 2.1 | 63 | Ausonia | 51.6 | S | 0.102 | 2.7 |
| 2 | Pallas | 266.0 | B | 13.402 | 2.5 | 65 | Cybele | 118.6 | C | 0.694 | 1.5 |
| 3 | Juno | 117.0 | Sk | 1.536 | 3.4 | 69 | Hesperia | 69.1 | M | 0.414 | 4.5 |
| 4 | Vesta | 265.0 | V | 17.630 | 3.4 | 78 | Diana | 60.3 | C | 0.085 | 1.4 |
| 5 | Astraea | 59.5 | S | 0.159 | 2.7 | 94 | Aurora | 102.4 | C | 0.414 | 1.4 |
| 6 | Hebe | 92.6 | S | 0.605 | 2.7 | 97 | Klotho | 41.4 | M | 0.089 | 4.5 |
| 7 | Iris | 99.9 | S | 0.796 | 2.9 | 98 | Ianthe | 52.2 | C | 0.055 | 1.4 |
| 8 | Flora | 67.9 | S | 0.236 | 2.7 | 105 | Artemis | 59.5 | C | 0.088 | 1.5 |
| 9 | Metis | 95.0 | S | 0.567 | 2.4 | 111 | Ate | 67.3 | C | 0.116 | 1.4 |
| 10 | Hygiea | 203.6 | C | 5.364 | 2.3 | 135 | Hertha | 39.6 | M | 0.078 | 4.5 |
| 11 | Parthenope | 77.7 | S | 0.356 | 2.7 | 139 | Juewa | 78.3 | C | 0.188 | 1.4 |
| 13 | Egeria | 103.8 | C | 0.412 | 1.3 | 145 | Adeona | 75.6 | C | 0.151 | 1.3 |
| 14 | Irene | 76.0 | S | 0.348 | 2.8 | 187 | Lamberta | 65.6 | C | 0.105 | 1.3 |
| 15 | Eunomia | 127.7 | S | 1.638 | 2.8 | 192 | Nausikaa | 51.6 | S | 0.107 | 2.8 |
| 16 | Psyche | 126.6 | M | 2.233 | 3.9 | 194 | Prokne | 84.2 | C | 0.182 | 1.1 |
| 18 | Melpomene | 70.3 | S | 0.267 | 2.7 | 216 | Kleopatra | 62.0 | M | 0.299 | 4.5 |
| 19 | Fortuna | 100.0 | Ch | 0.463 | 1.7 | 230 | Athamantis | 54.5 | S | 0.126 | 2.8 |
| 20 | Massalia | 72.8 | S | 0.291 | 2.7 | 324 | Bamberga | 114.5 | CP | 0.661 | 1.6 |
| 21 | Lutetia | 47.9 | M | 0.139 | 4.5 | 337 | Devosa | 29.6 | M | 0.033 | 4.5 |
| 22 | Kalliope | 90.5 | M | 0.491 | 2.4 | 344 | Desiderata | 66.1 | C | 0.114 | 1.4 |
| 23 | Thalia | 53.8 | S | 0.129 | 3.0 | 354 | Eleonora | 77.6 | S1 | 0.327 | 2.5 |
| 24 | Themis | 99.0 | C | 0.403 | 1.5 | 372 | Palma | 94.3 | C | 0.355 | 1.5 |
| 25 | Phocaea | 37.6 | S | 0.040 | 2.7 | 405 | Thia | 62.5 | C | 0.092 | 1.4 |
| 27 | Euterpe | 48.0 | S | 0.084 | 2.7 | 409 | Aspasia | 80.8 | C | 0.216 | 1.5 |
| 28 | Bellona | 60.5 | S | 0.165 | 2.7 | 419 | Aurelia | 64.5 | C | 0.102 | 1.4 |
| 29 | Amphitrite | 106.1 | S | 0.906 | 2.7 | 451 | Patientia | 112.5 | C | 0.610 | 1.5 |
| 30 | Urania | 49.8 | S | 0.095 | 2.7 | 488 | Kreusa | 75.1 | C | 0.164 | 1.4 |
| 31 | Euphrosyne | 128.0 | C | 1.139 | 1.9 | 511 | Davida | 163.0 | C | 1.638 | 1.4 |
| 41 | Daphne | 87.0 | Ch | 0.527 | 2.9 | 532 | Herculina | 111.1 | S | 0.886 | 2.3 |
| 42 | Isis | 50.1 | S | 0.092 | 2.6 | 554 | Peraga | 47.9 | C | 0.044 | 1.4 |
| 45 | Eugenia | 107.3 | C | 0.397 | 1.2 | 654 | Zelinda | 63.7 | Ch | 0.090 | 1.2 |
| 51 | Nemusa | 73.9 | C | 0.144 | 1.3 | 704 | Interamnia | 158.3 | C | 2.464 | 2.2 |
| 52 | Europa | 151.3 | C | 1.354 | 1.4 | 747 | Winchester | 85.9 | C | 0.196 | 1.1 |
| 60 | Echo | 30.1 | S | 0.021 | 2.7 | | | | | | |

Table A2: Estimated densities ρ in gm/cm^3 of ‘minor’ asteroids

| Type | ρ |
|------|--------|
| C | 1.093 |
| S | 3.452 |
| M | 4.221 |

Table A3: Parameters of ‘minor’ asteroids: type and radius r in km.
 (Continued on next page.)

| | | | | | | | | |
|---------------|---|-------|-----------------|---|-------|----------------|---|------|
| 12 Victoria | S | 56.4 | 92 Undina | M | 63.2 | 171 Ophelia | C | 58.3 |
| 17 Thetis | S | 45.0 | 93 Minerva | C | 70.5 | 172 Baucis | S | 31.2 |
| 26 Proserpina | S | 47.5 | 95 Arethusa | C | 68.0 | 173 Ino | C | 77.1 |
| 32 Pomona | S | 40.4 | 96 Aegle | C | 85.0 | 175 Andromache | C | 50.5 |
| 34 Circe | C | 56.8 | 99 Dike | C | 36.0 | 176 Iduna | C | 60.5 |
| 35 Leukothea | C | 51.6 | 100 Hekate | S | 44.3 | 177 Irma | C | 36.6 |
| 36 Atalante | C | 52.8 | 102 Miriam | C | 41.5 | 181 Eucharis | S | 53.0 |
| 37 Fides | S | 54.2 | 103 Hera | S | 45.6 | 185 Eunike | C | 78.8 |
| 38 Leda | C | 58.0 | 104 Klymene | C | 61.8 | 191 Kolga | C | 50.5 |
| 39 Laetitia | S | 74.8 | 106 Dione | C | 73.3 | 195 Eurykleia | C | 42.9 |
| 40 Harmonia | S | 53.8 | 107 Camilla | C | 111.3 | 196 Philomela | S | 68.2 |
| 43 Ariadne | S | 32.9 | 109 Felicitas | C | 44.7 | 198 Ampella | S | 28.6 |
| 44 Nysa | S | 35.3 | 110 Lydia | M | 43.0 | 200 Dynamene | C | 64.2 |
| 46 Hestia | C | 62.1 | 112 Iphigenia | C | 36.1 | 201 Penelope | M | 34.2 |
| 47 Aglaja | C | 63.5 | 113 Amalthea | S | 23.1 | 203 Pompeja | C | 58.1 |
| 48 Doris | C | 110.9 | 114 Kassandra | C | 49.8 | 205 Martha | C | 40.5 |
| 49 Pales | C | 74.9 | 115 Thyra | S | 39.9 | 206 Hersilia | C | 56.5 |
| 50 Virginia | C | 49.9 | 117 Lomia | C | 74.4 | 209 Dido | C | 80.0 |
| 53 Kalypso | C | 57.7 | 118 Peitho | S | 20.9 | 210 Isabella | C | 43.3 |
| 54 Alexandra | C | 82.9 | 120 Lachesis | C | 87.1 | 211 Isolda | C | 71.6 |
| 56 Melete | C | 56.6 | 121 Hermione | C | 104.5 | 212 Medea | C | 68.1 |
| 57 Mnemosyne | S | 56.3 | 124 Alkestete | S | 38.2 | 213 Lilaea | C | 41.5 |
| 58 Concordia | C | 46.7 | 127 Johanna | C | 61.0 | 221 Eos | S | 51.9 |
| 59 Elpis | C | 82.4 | 128 Nemesis | C | 94.1 | 223 Rosa | C | 43.8 |
| 62 Erato | C | 47.7 | 129 Antigone | M | 56.5 | 224 Oceana | M | 30.9 |
| 68 Leto | S | 61.3 | 130 Elektra | C | 91.1 | 225 Henrietta | C | 60.2 |
| 70 Panopaea | C | 61.1 | 132 Aethra | M | 21.3 | 227 Philosophi | C | 43.7 |
| 71 Niobe | S | 41.7 | 134 Sophrosyne | C | 54.0 | 233 Asterope | C | 51.4 |
| 72 Feronia | C | 43.1 | 137 Meliboea | C | 72.7 | 236 Honoria | S | 43.1 |
| 74 Galatea | C | 59.4 | 140 Siwa | C | 54.9 | 238 Hypatia | C | 74.2 |
| 75 Eurydike | M | 27.8 | 141 Lumen | C | 65.5 | 240 Vanadis | C | 52.0 |
| 76 Freia | C | 91.8 | 143 Adria | C | 45.0 | 241 Germania | C | 84.5 |
| 77 Frigga | M | 34.6 | 144 Vibilia | C | 70.9 | 247 Eukrate | C | 67.2 |
| 79 Eurynome | S | 33.2 | 146 Lucina | C | 66.1 | 250 Bettina | M | 39.9 |
| 80 Sappho | S | 39.2 | 147 Protogeneia | C | 66.5 | 259 Aletheia | C | 89.3 |
| 81 Terpsichor | C | 59.5 | 148 Gallia | S | 48.9 | 266 Aline | C | 54.5 |
| 82 Alkmene | S | 30.5 | 150 Nuwa | C | 75.6 | 268 Adorea | C | 69.9 |
| 83 Beatrix | C | 40.7 | 154 Bertha | C | 92.5 | 275 Sapientia | C | 51.5 |
| 84 Klio | C | 39.6 | 156 Xanthippe | C | 60.5 | 276 Adelheid | C | 60.8 |
| 85 Io | C | 77.4 | 159 Aemilia | C | 62.5 | 283 Emma | C | 74.0 |
| 86 Semele | C | 60.3 | 160 Una | C | 40.6 | 287 Nephthys | S | 33.8 |
| 87 Sylvia | C | 130.5 | 162 Laurentia | C | 49.6 | 303 Josephina | C | 49.6 |
| 88 Thisbe | C | 116.0 | 163 Erigone | C | 36.3 | 304 Olga | C | 33.9 |
| 89 Julia | S | 75.7 | 164 Eva | C | 52.5 | 308 Polyxo | C | 70.3 |
| 90 Antiope | C | 60.0 | 165 Loreley | C | 77.6 | 313 Chaldaea | C | 48.2 |
| 91 Aegina | C | 54.9 | 168 Sibylla | C | 74.2 | 322 Phaeo | M | 35.4 |

Table A3 (continued): Parameters of ‘minor’ asteroids: type and radius r in km.

| ID | Name | Type | r | ID | Name | Type | r | ID | Name | Type | r |
|-----|-------------|------|-------|-----|--------------|------|-------|------|-------------|------|-------|
| 326 | Tamara | C | 46.5 | 445 | Edna | C | 43.6 | 667 | Denise | C | 40.6 |
| 328 | Gudrun | S | 61.5 | 449 | Hamburga | C | 42.8 | 674 | Rachele | S | 48.7 |
| 329 | Svea | C | 38.9 | 454 | Mathesis | C | 40.8 | 675 | Ludmilla | S | 38.0 |
| 334 | Chicago | C | 77.9 | 455 | Bruchsalia | C | 42.2 | 680 | Genoveva | C | 42.0 |
| 335 | Roberta | C | 44.5 | 464 | Megaira | C | 37.0 | 683 | Lanzia | C | 41.0 |
| 336 | Lacadiera | C | 34.6 | 465 | Alekto | C | 36.7 | 690 | Wratislavi. | C | 67.5 |
| 338 | Budrosa | M | 31.6 | 466 | Tisiphone | C | 57.8 | 691 | Lehigh | C | 43.8 |
| 345 | Tercidina | C | 47.1 | 469 | Argentina | C | 62.8 | 694 | Ekard | C | 45.4 |
| 346 | Hermentari. | S | 53.3 | 471 | Papagena | S | 67.1 | 696 | Leonora | C | 37.9 |
| 347 | Pariana | M | 25.6 | 476 | Hedwig | C | 58.4 | 702 | Alauda | C | 97.4 |
| 349 | Dembowska | S | 69.9 | 481 | Emita | C | 116.0 | 705 | Erminia | C | 67.1 |
| 350 | Ornamenta | C | 59.2 | 485 | Genua | S | 31.9 | 709 | Fringilla | C | 48.3 |
| 356 | Liguria | C | 65.7 | 489 | Comacina | C | 69.7 | 712 | Boliviana | C | 63.8 |
| 357 | Ninina | C | 53.0 | 490 | Veritas | C | 57.8 | 713 | Luscinia | C | 52.8 |
| 358 | Apollonia | C | 44.7 | 491 | Carina | C | 48.7 | 735 | Marghanna | C | 37.2 |
| 360 | Carlova | C | 57.9 | 498 | Tokio | C | 41.4 | 739 | Mandeville | C | 53.7 |
| 362 | Havnia | C | 49.0 | 503 | Evelyn | C | 40.8 | 740 | Cantabia | C | 45.4 |
| 363 | Padua | C | 48.5 | 505 | Cava | C | 57.5 | 751 | Faina | C | 55.3 |
| 365 | Corduba | C | 53.0 | 506 | Marion | C | 53.0 | 752 | Sulamitis | M | 31.4 |
| 366 | Vincentina | C | 46.9 | 508 | Princetonia | C | 71.2 | 760 | Massinga | S | 35.6 |
| 369 | Aeria | M | 30.0 | 514 | Armida | C | 53.1 | 762 | Pulcova | C | 68.5 |
| 373 | Melusina | C | 47.9 | 516 | Amherstia | M | 36.5 | 769 | Tatjana | C | 53.2 |
| 375 | Ursula | C | 108.0 | 517 | Edith | M | 45.6 | 772 | Tanete | C | 58.8 |
| 377 | Campania | C | 45.5 | 521 | Brixia | C | 57.8 | 773 | Irmtraud | C | 47.9 |
| 381 | Myrrha | C | 60.3 | 535 | Montague | C | 37.2 | 776 | Berbericia | C | 75.6 |
| 385 | Ilmatar | S | 45.8 | 536 | Merapi | C | 75.7 | 778 | Theobalda | C | 32.0 |
| 386 | Siegena | C | 82.5 | 545 | Messalina | C | 55.6 | 780 | Armenia | C | 47.2 |
| 387 | Aquitania | S | 50.3 | 547 | Praxedis | M | 34.8 | 784 | Pickeringi. | C | 44.7 |
| 388 | Charybdis | C | 57.1 | 566 | Stereoskopia | C | 84.1 | 786 | Bredichina | C | 45.8 |
| 389 | Industria | S | 39.5 | 568 | Cheruskia | C | 43.5 | 788 | Hohenstein. | C | 51.8 |
| 393 | Lampetia | C | 48.4 | 569 | Misa | C | 36.5 | 790 | Pretoria | C | 85.2 |
| 404 | Arsinoe | C | 48.8 | 584 | Semiramis | S | 27.0 | 791 | Ani | C | 51.8 |
| 407 | Arachne | C | 47.5 | 585 | Bilkis | C | 29.1 | 804 | Hispania | C | 78.6 |
| 410 | Chloris | C | 61.8 | 591 | Irmgard | M | 25.9 | 814 | Tauris | C | 54.8 |
| 412 | Elisabetha | C | 45.5 | 593 | Titania | C | 37.7 | 849 | Ara | M | 30.9 |
| 415 | Palatia | C | 38.2 | 595 | Polyxena | C | 54.5 | 895 | Helio | C | 71.0 |
| 416 | Vaticana | S | 42.7 | 596 | Scheila | C | 56.7 | 909 | Ulla | C | 58.2 |
| 420 | Bertholda | C | 70.6 | 598 | Octavia | C | 36.2 | 914 | Palisana | C | 38.3 |
| 423 | Diotima | C | 104.4 | 599 | Luisa | S | 32.4 | 980 | Anacostia | S | 43.1 |
| 424 | Gratia | C | 43.6 | 602 | Marianna | C | 62.4 | 1015 | Christa | C | 48.5 |
| 426 | Hippo | C | 63.5 | 604 | Tekmessia | M | 32.6 | 1021 | Flammario | C | 49.7 |
| 431 | Nephelle | C | 47.5 | 618 | Elfriede | C | 60.1 | 1036 | Ganymed | S | 15.8 |
| 432 | Pythia | S | 23.4 | 623 | Chimaera | C | 22.1 | 1093 | Freda | C | 58.4 |
| 433 | Eros | S | 9.7 | 626 | Notburga | C | 50.4 | 1107 | Lictoria | M | 39.6 |
| 442 | Eichsfeldi. | C | 32.9 | 635 | Vundtia | C | 49.1 | 1171 | Rusthaweli. | C | 35.1 |
| 444 | Gyptis | C | 79.8 | 663 | Gerlinde | C | 50.4 | 1467 | Mashona | C | 112.0 |

Appendix B. Measurement Residual Plots

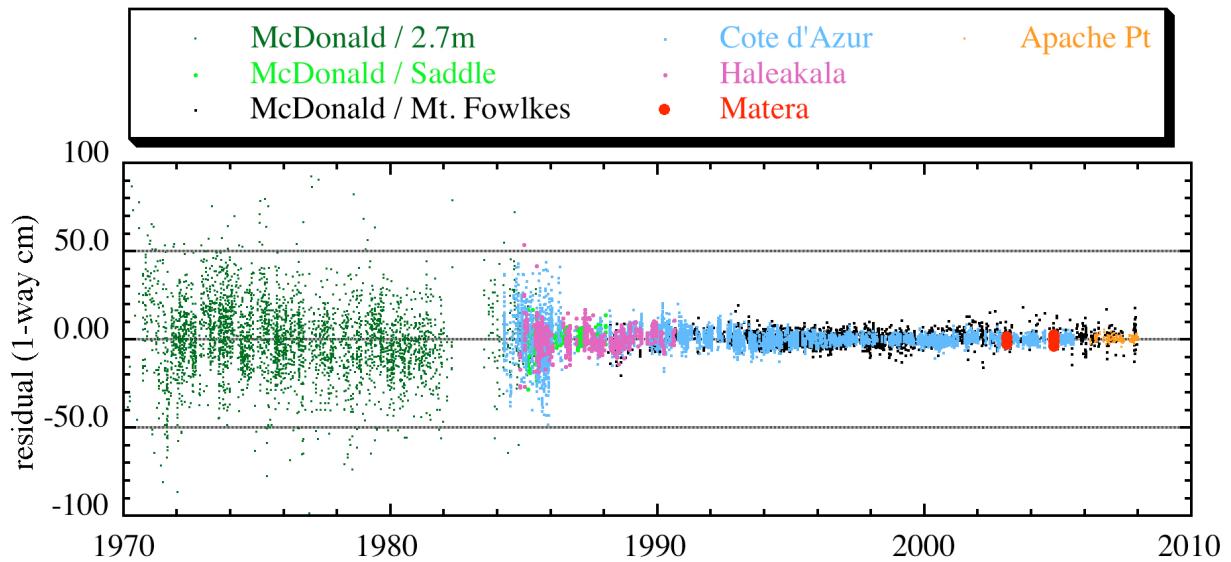


Figure B-1: Lunar laser ranging residuals.

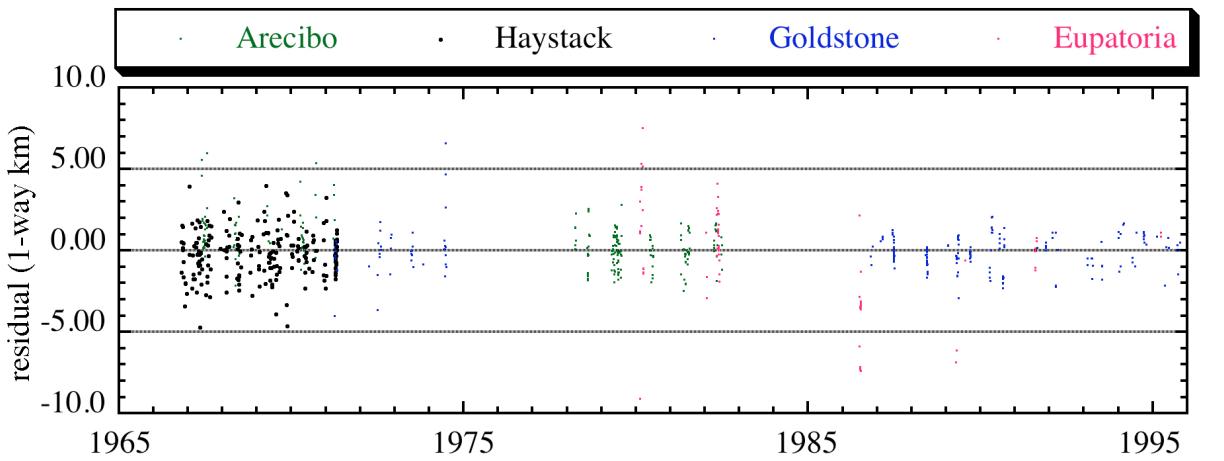


Figure B-2: Mercury radar range residuals.

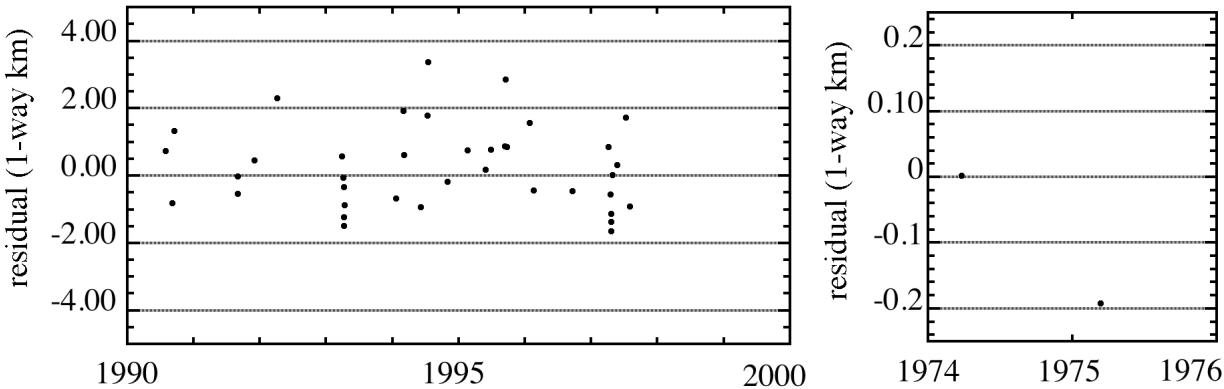


Figure B-3: a) Mercury radar closure residuals. b) Mariner 10 range residuals at Mercury

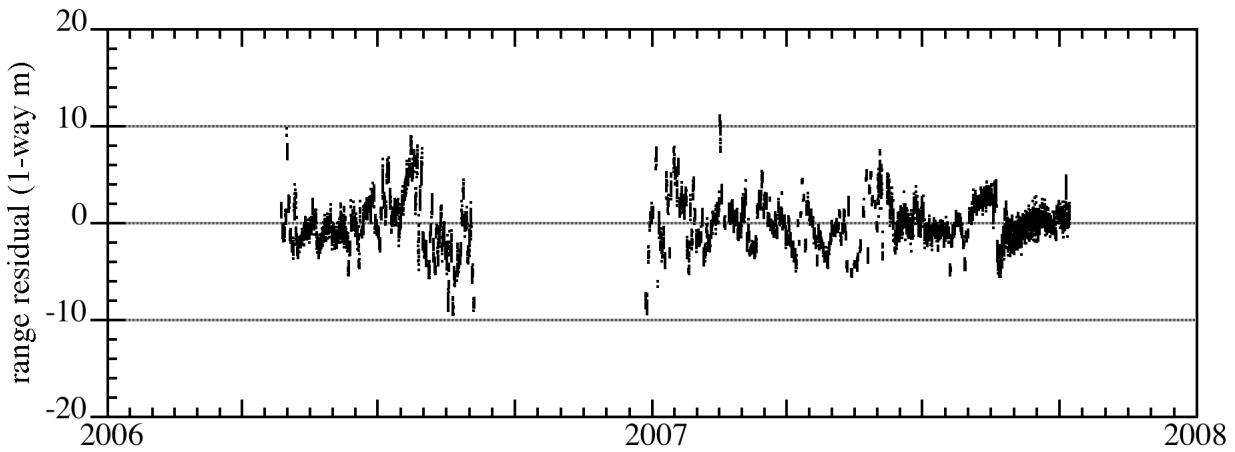


Figure B-4: Venus Express range residuals.

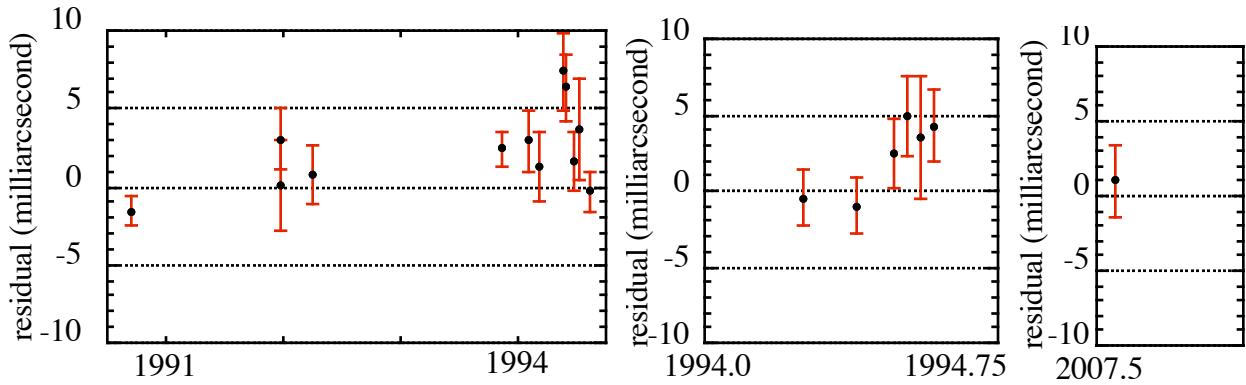


Figure B-5: Venus spacecraft VLBI residuals: a) Magellan from Goldstone-Canberra baseline; b) Magellan from Goldstone-Madrid baseline; c) Venus Express from Goldstone-Madrid baseline.

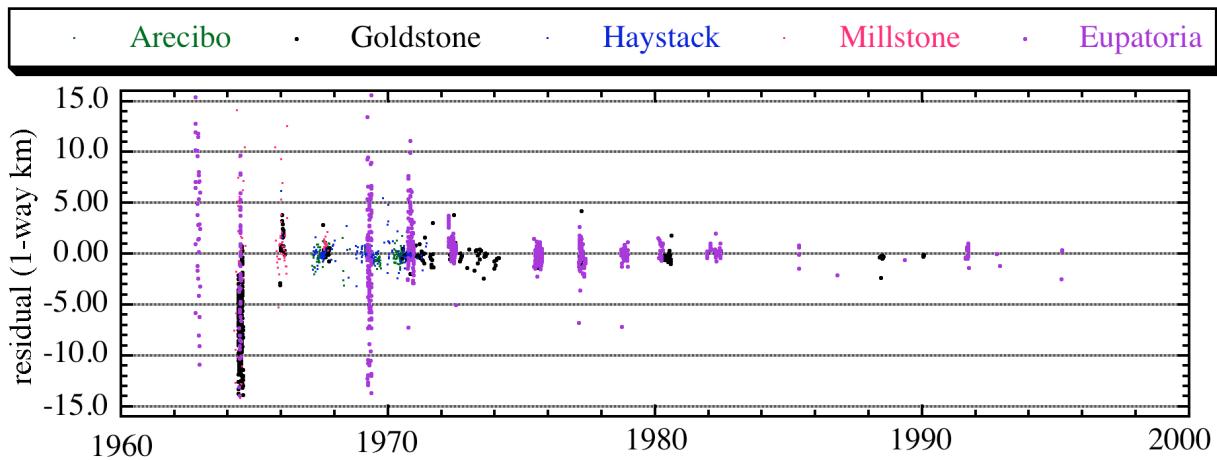


Figure B-6: Venus radar range residuals.

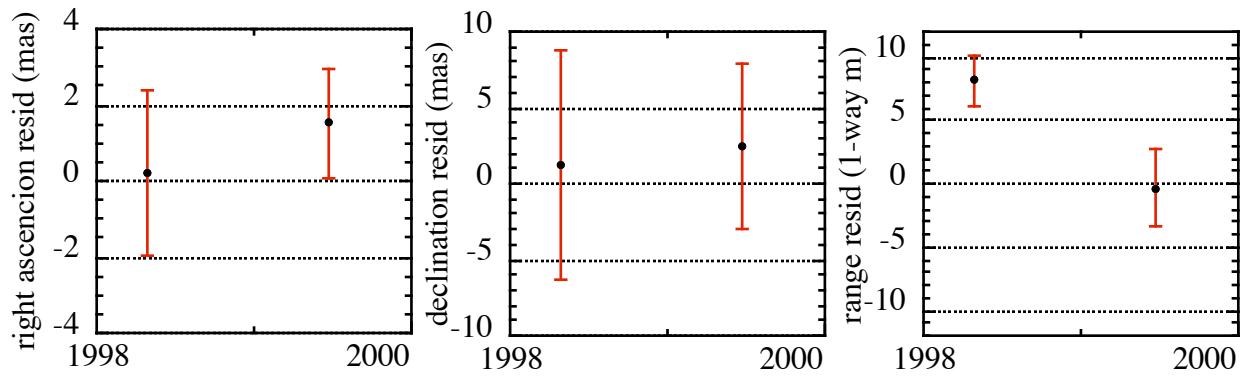


Figure B-7: Residuals for Cassini encounters at Venus.

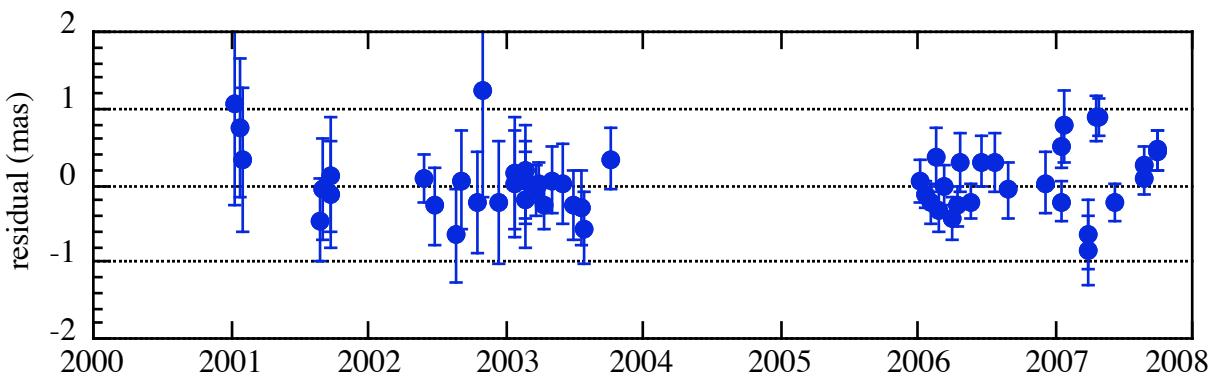


Figure B-8: Residuals for Mars spacecraft VLBI on Goldstone-Canberra baseline.

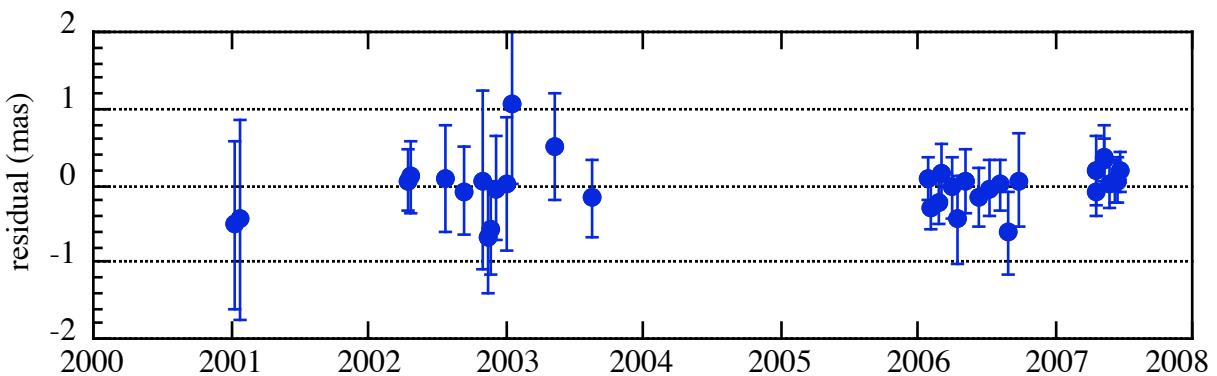


Figure B-9: Residuals for Mars spacecraft VLBI on Goldstone-Madrid baseline.

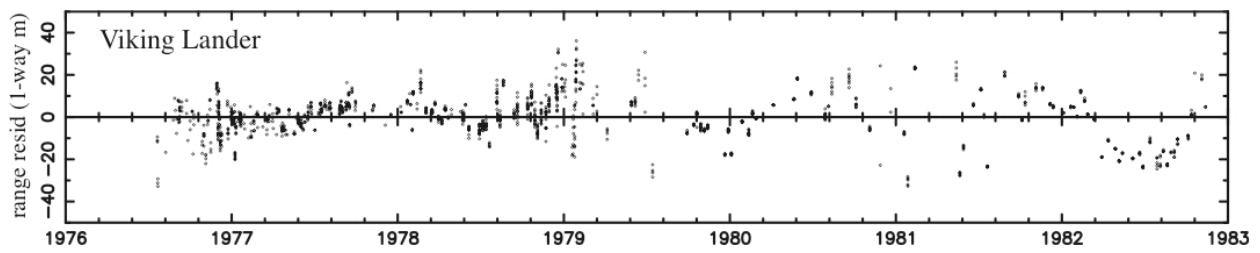


Figure B-10: Viking Lander range residuals.

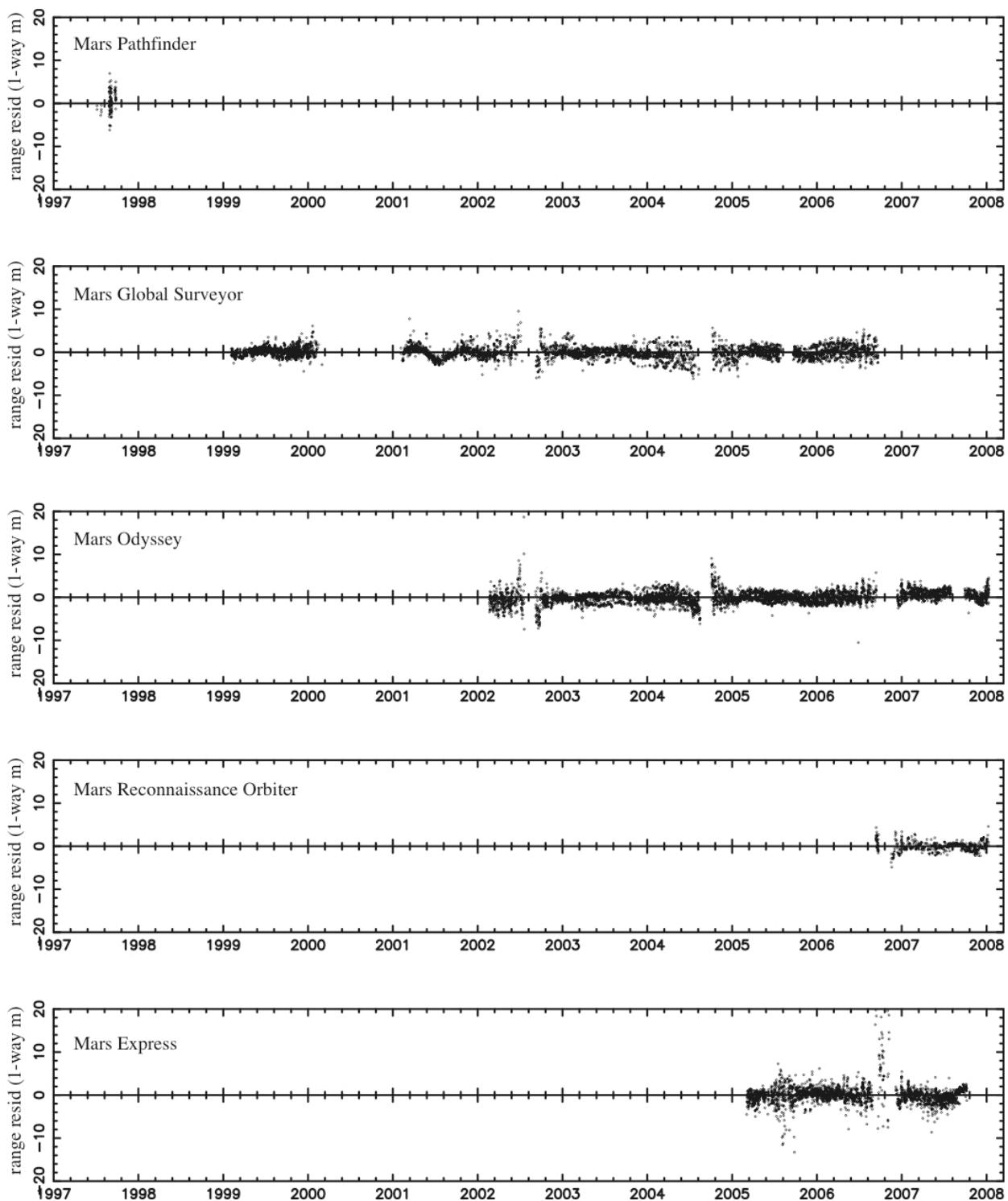


Figure B-11: Post-Viking Mars spacecraft range residuals.

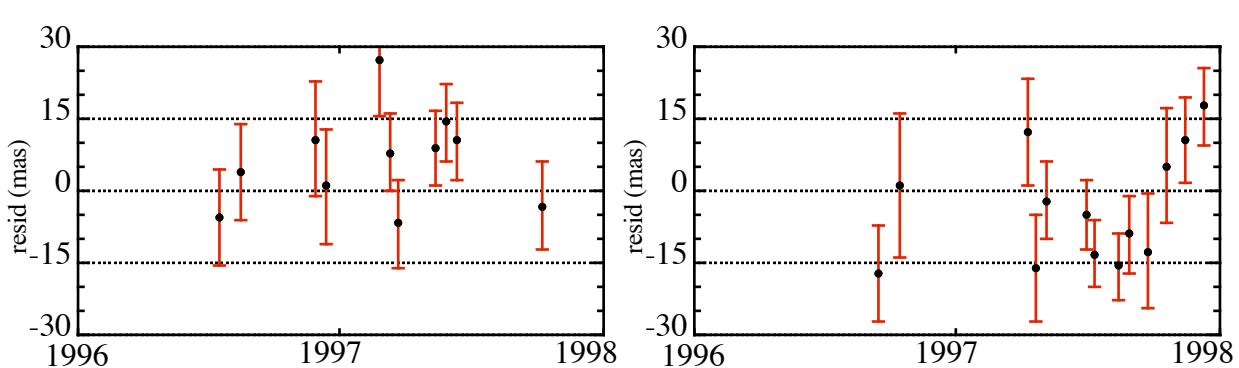
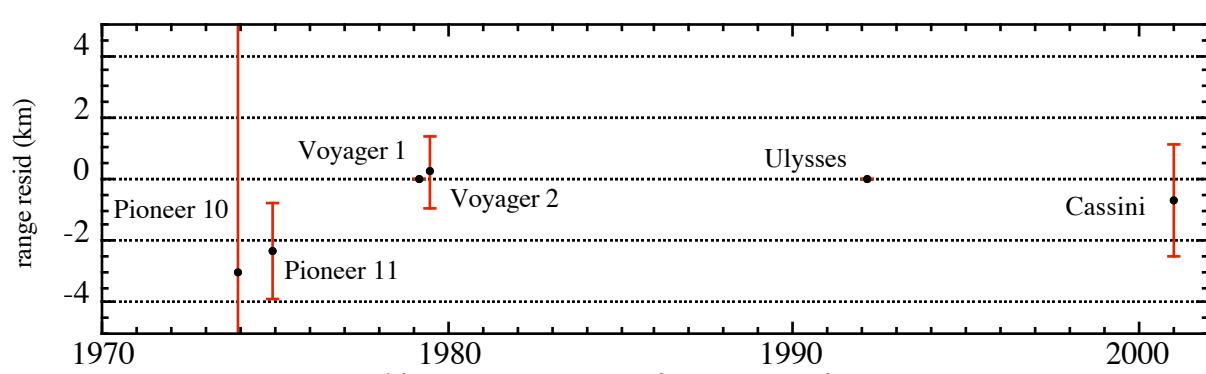
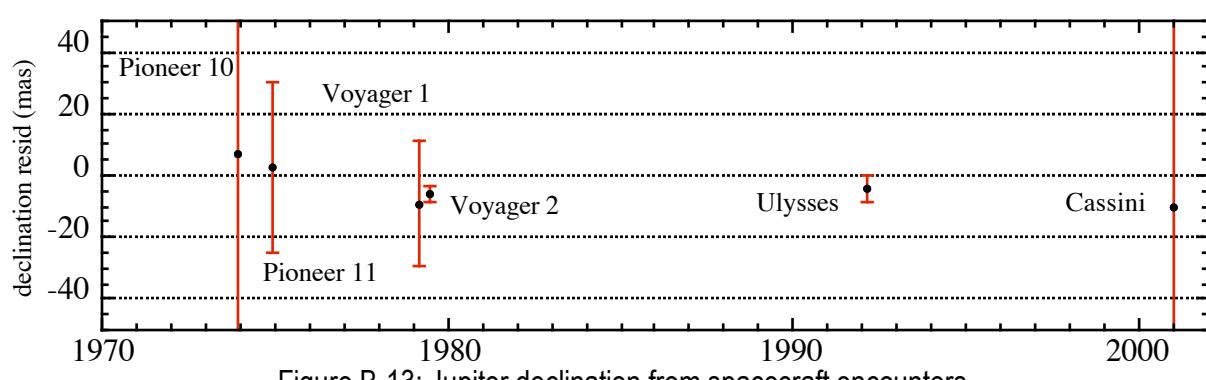
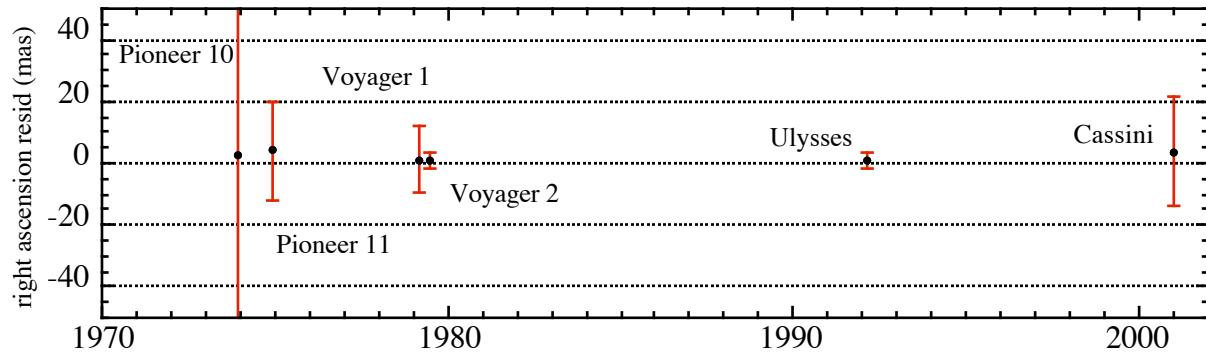


Figure B-15: VLBI observations of Galileo at Jupiter on a) Goldstone-Canberra baseline and b) Goldstone-Madrid baseline.

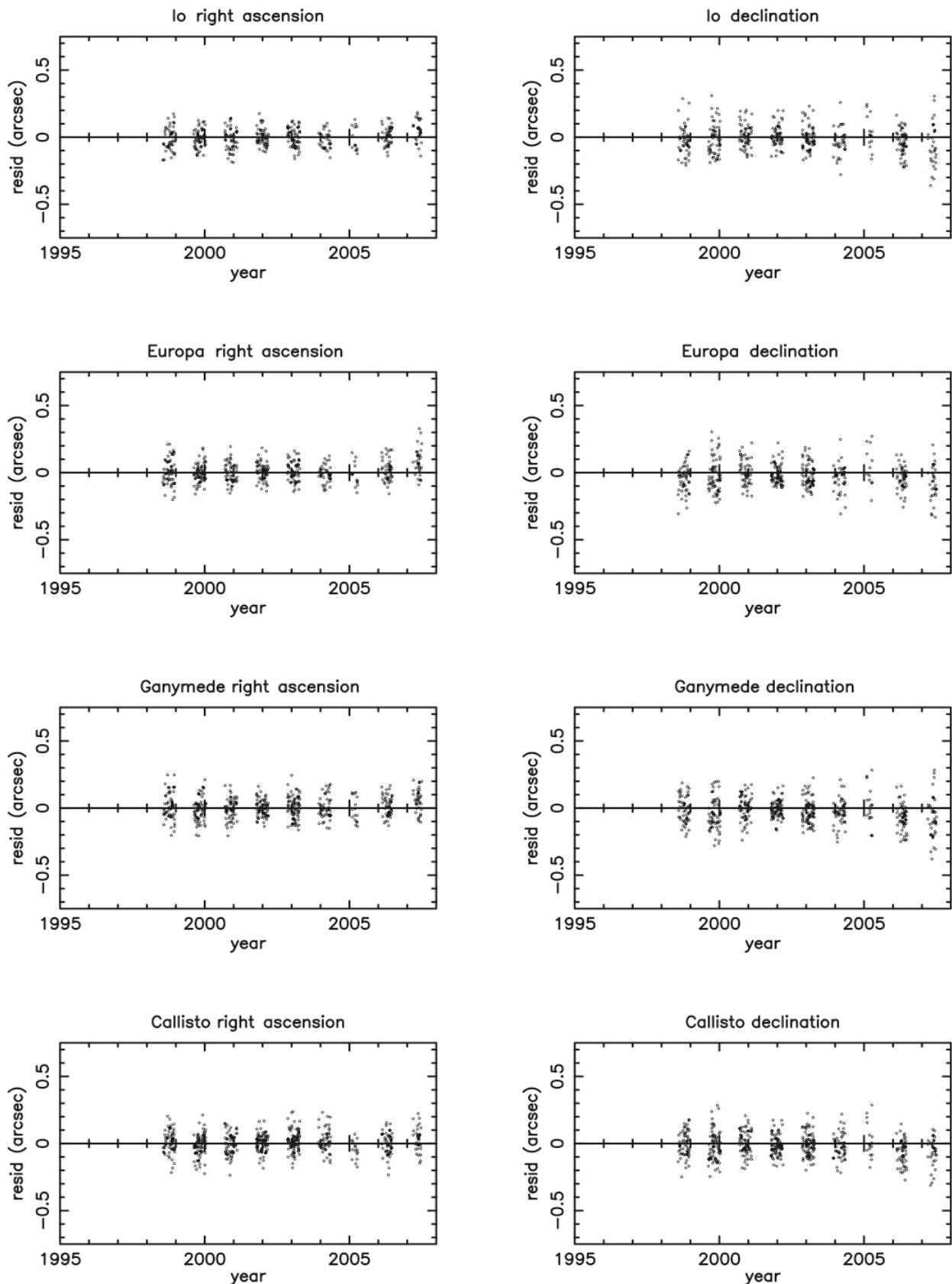


Figure B-16: Observations of Galilean satellites from US Naval Observatory, Flagstaff.

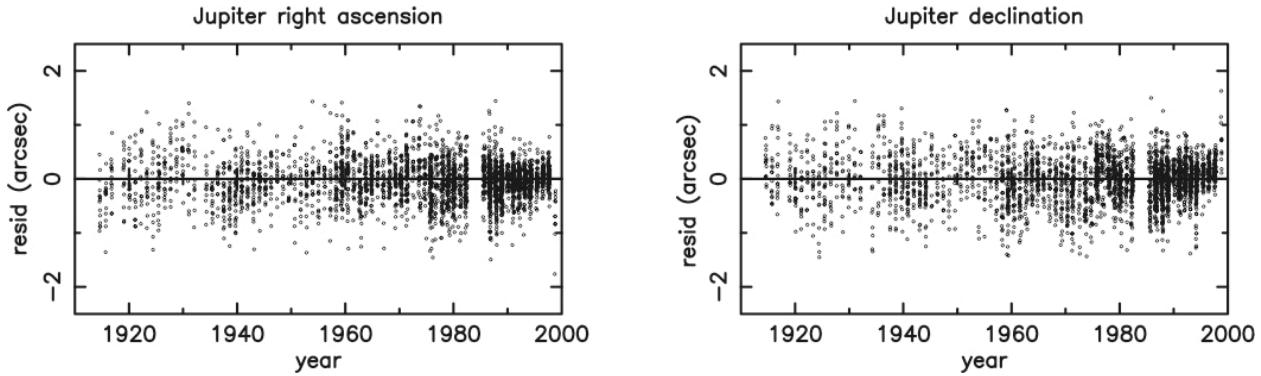


Figure B-17: Transit observations of Jupiter

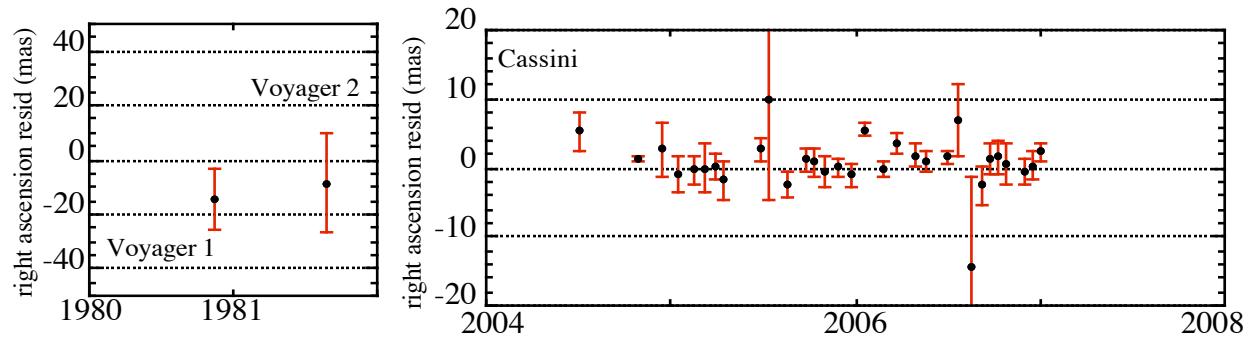


Figure B-18: Saturn right ascension from Voyage 1&2 and Cassini tracking analysis.

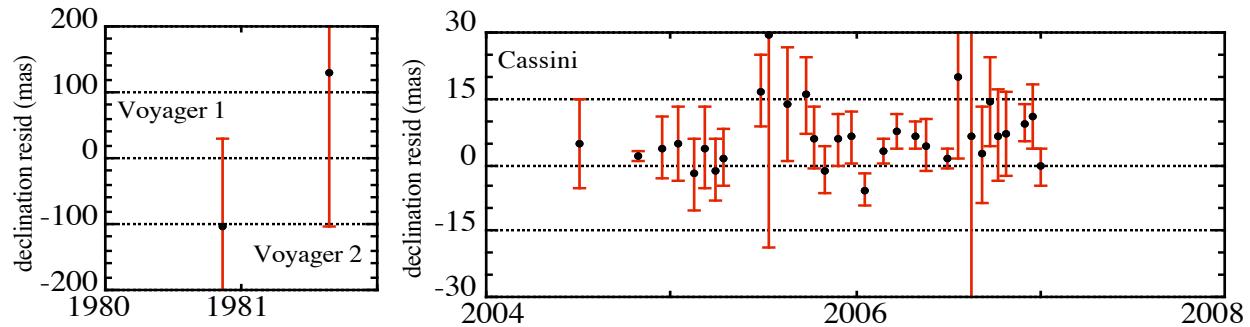


Figure B-19: Saturn declination from spacecraft encounters.

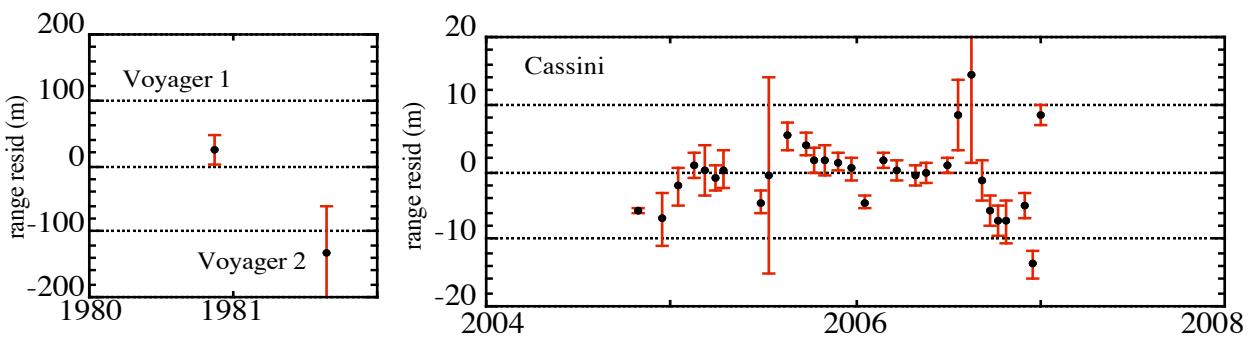


Figure B-20: Saturn-Earth range from spacecraft encounters.

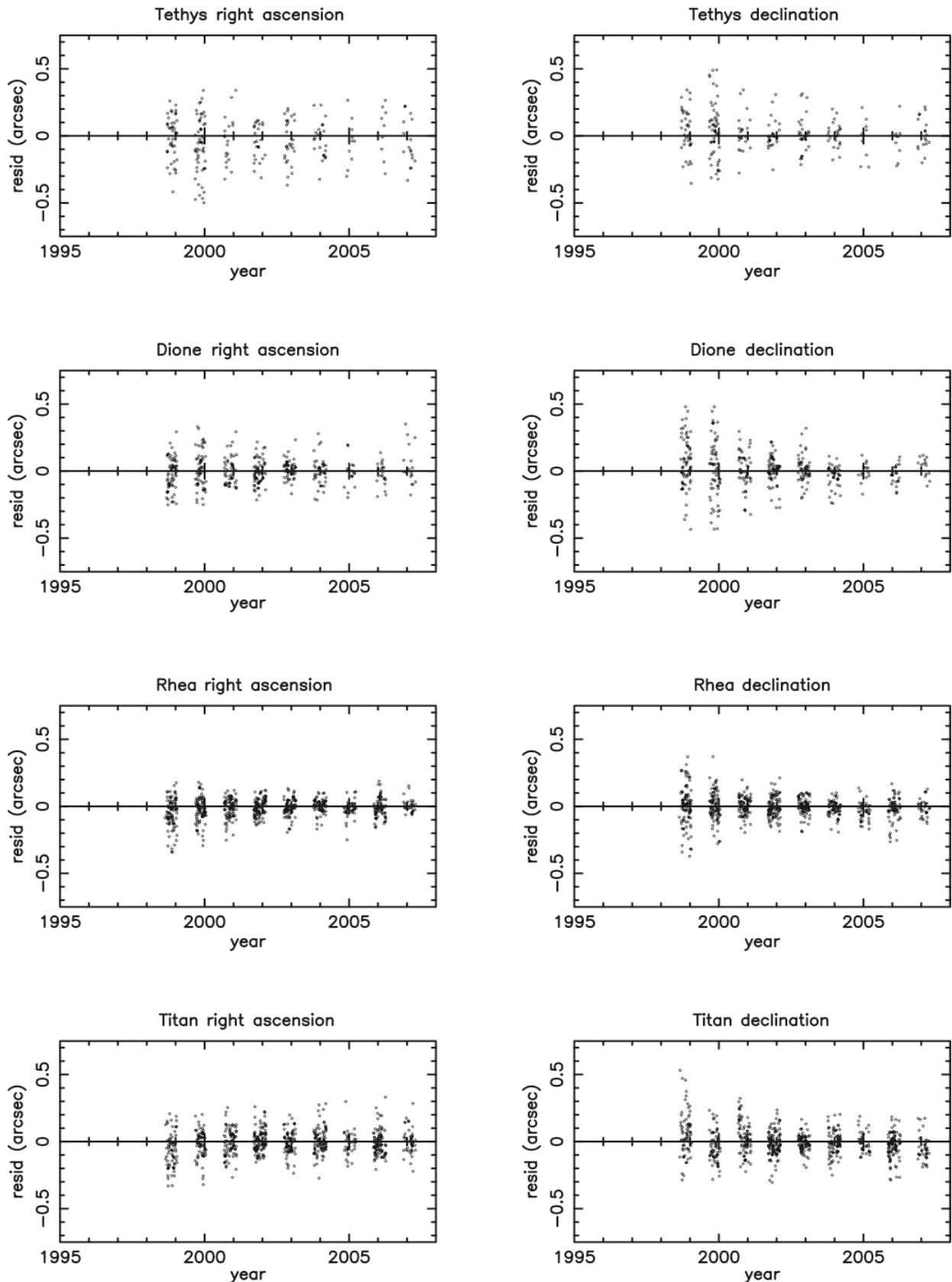


Figure B-21: Saturn satellite (3-6) observations from US Naval Observatory, Flagstaff.

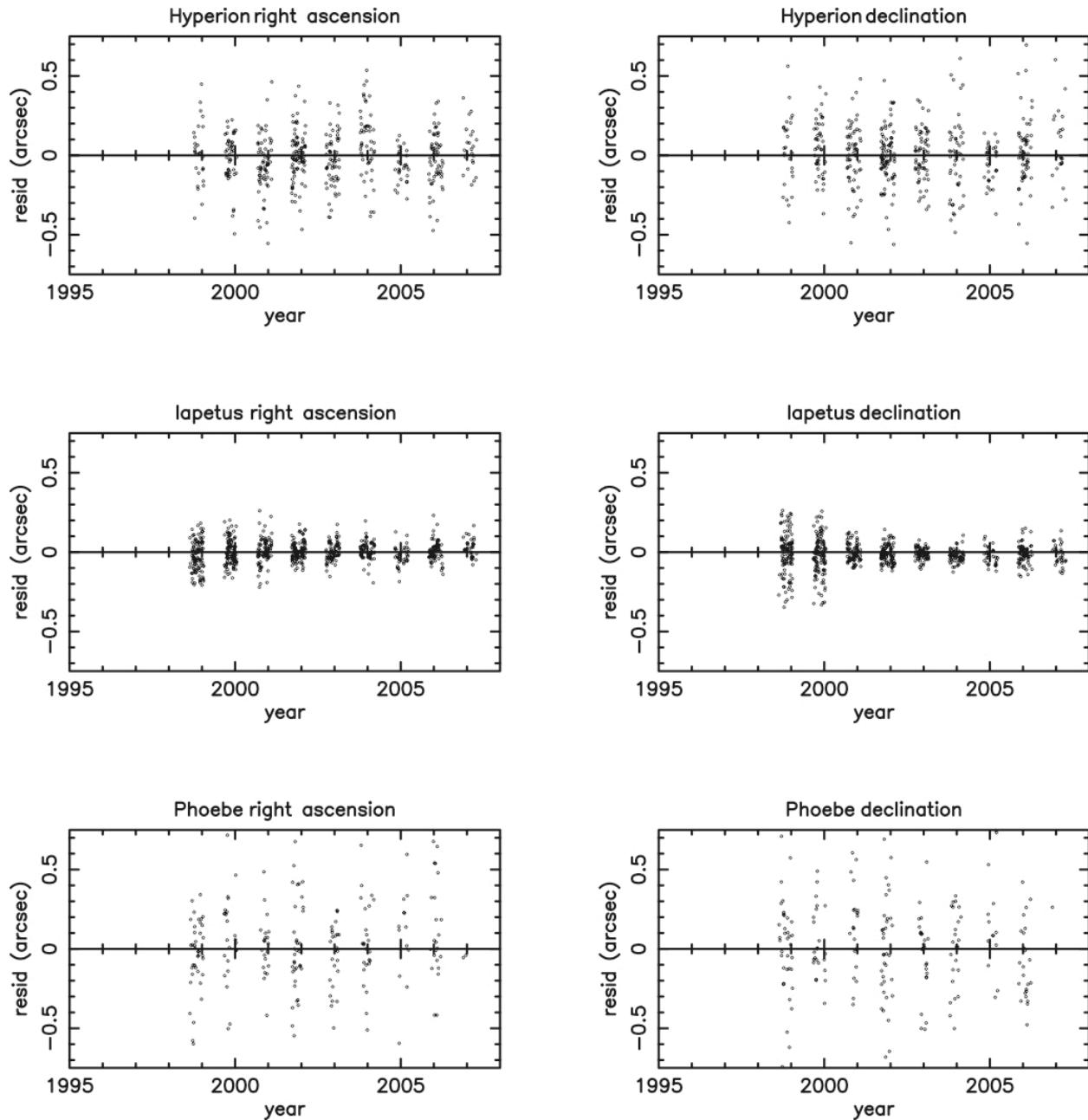


Figure B-22: Saturn satellite (7-9) observations from US Naval Observatory, Flagstaff.

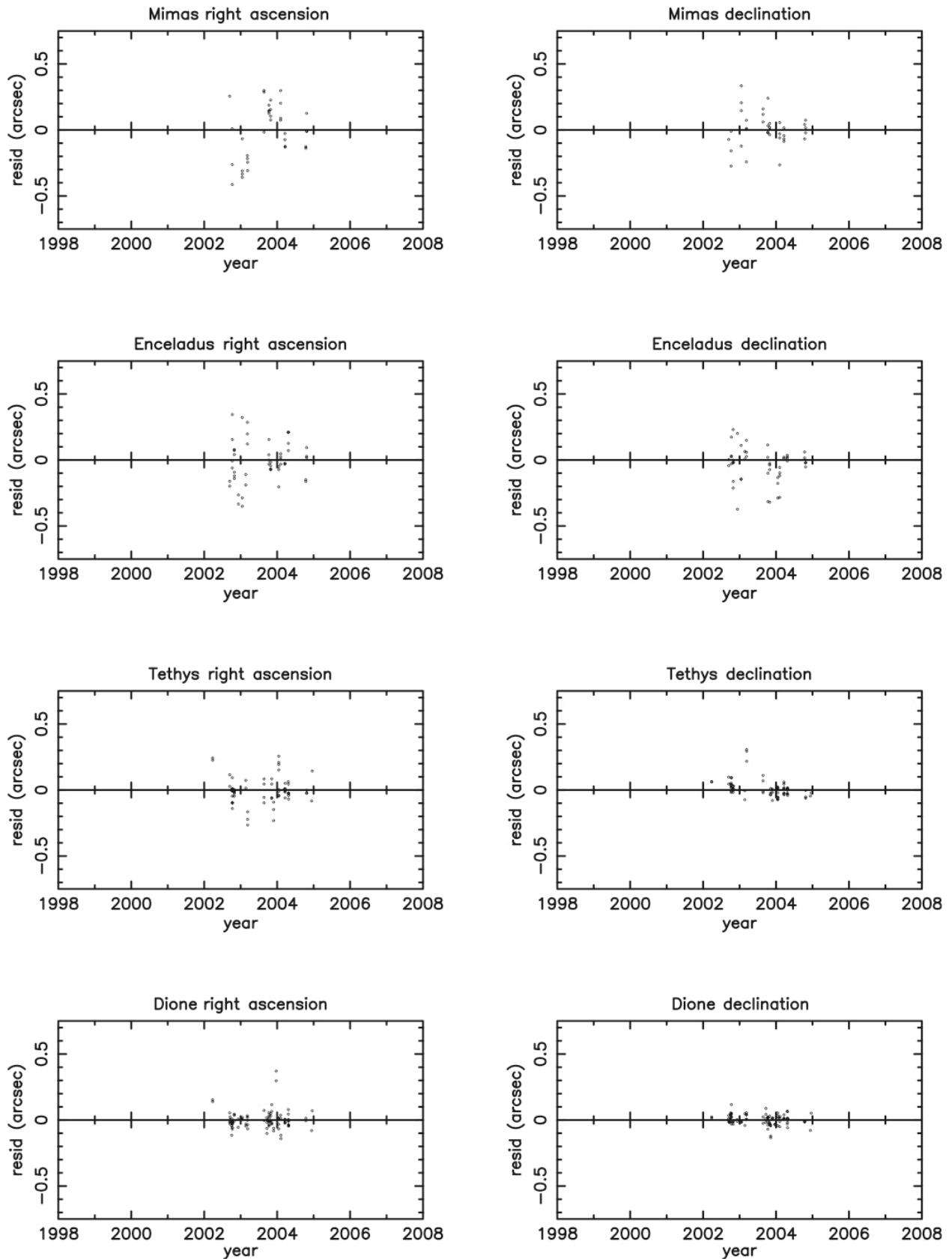


Figure B-23: Saturn satellite (1-4) observations from Table Mountain Observatory.

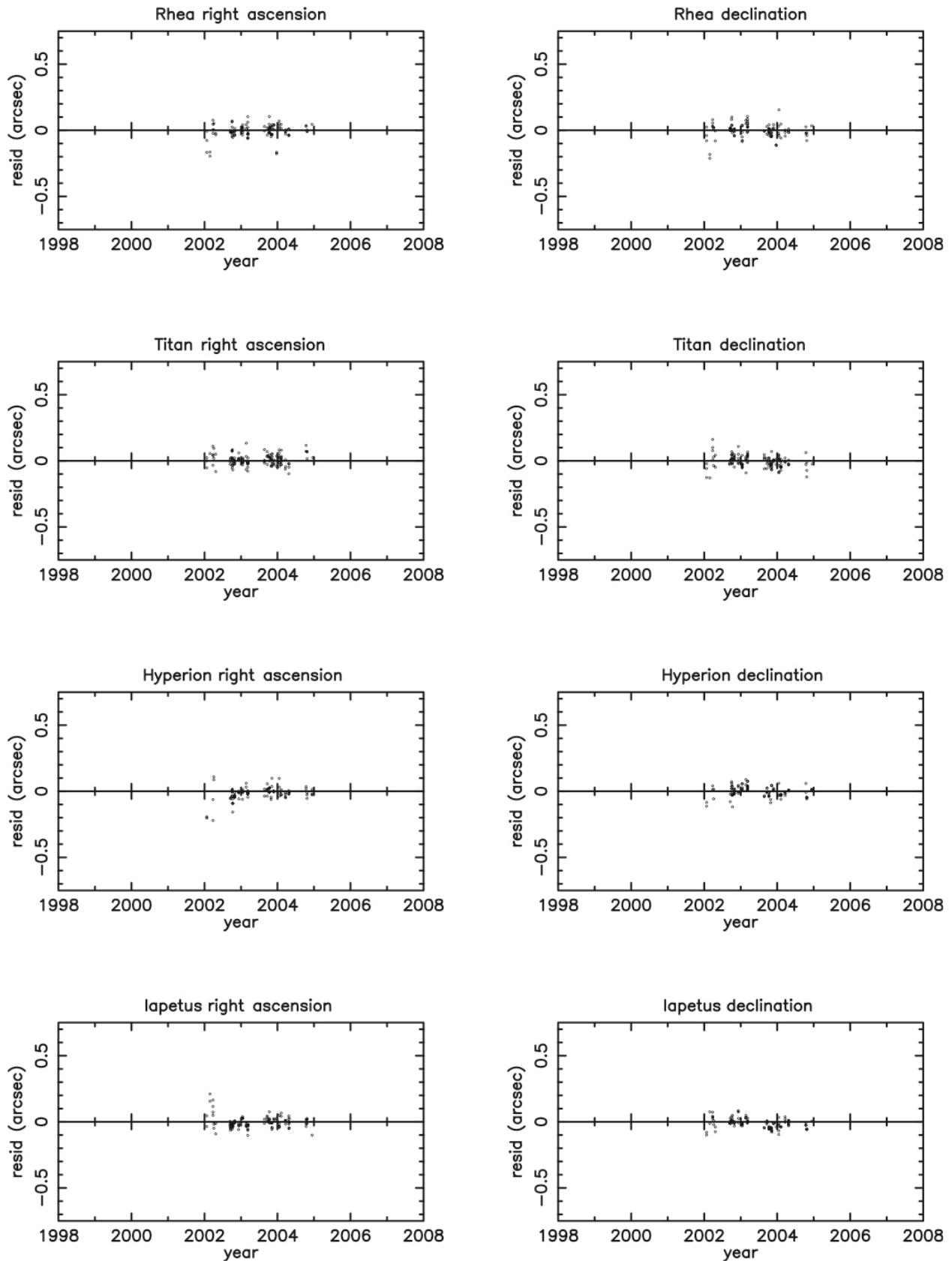


Figure B-24: Saturn satellite (5-8) observations from Table Mountain Observatory.

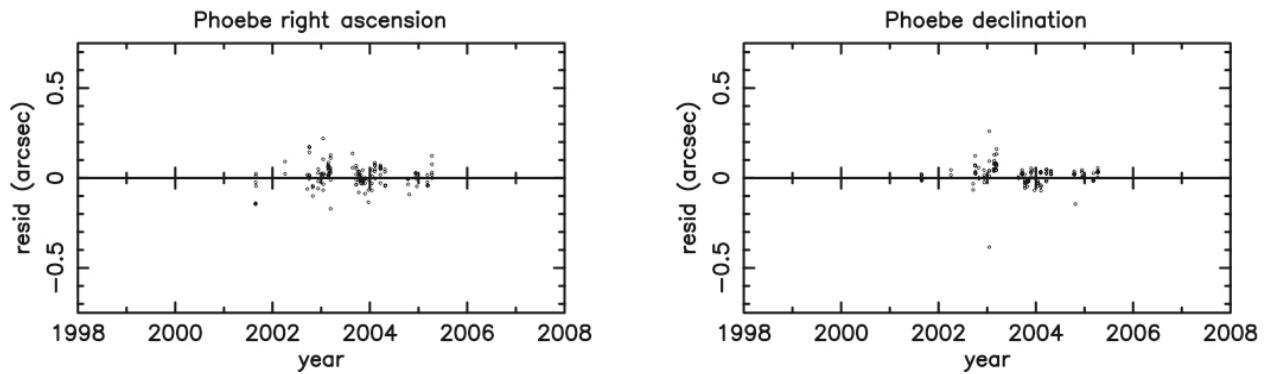


Figure B-25: Saturn satellite (9) observations from Table Mountain Observatory.

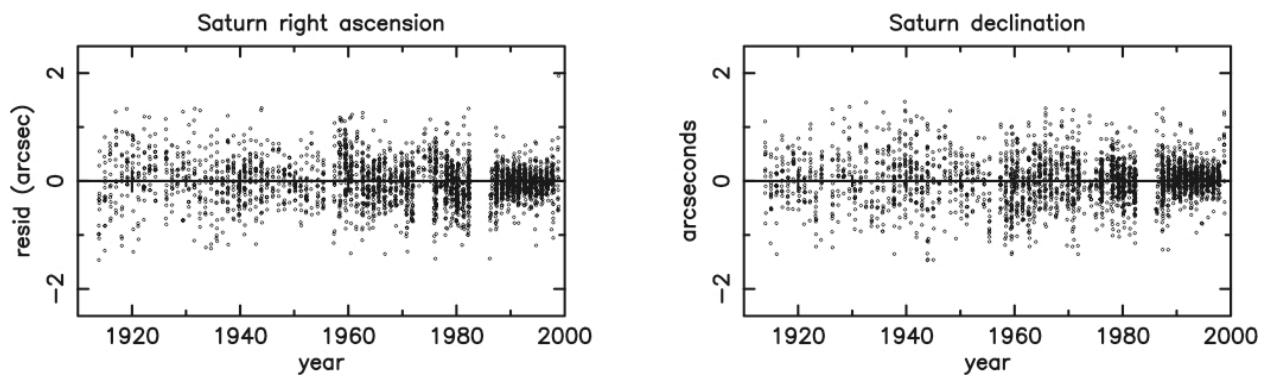


Figure B-26: Transit observations of Saturn

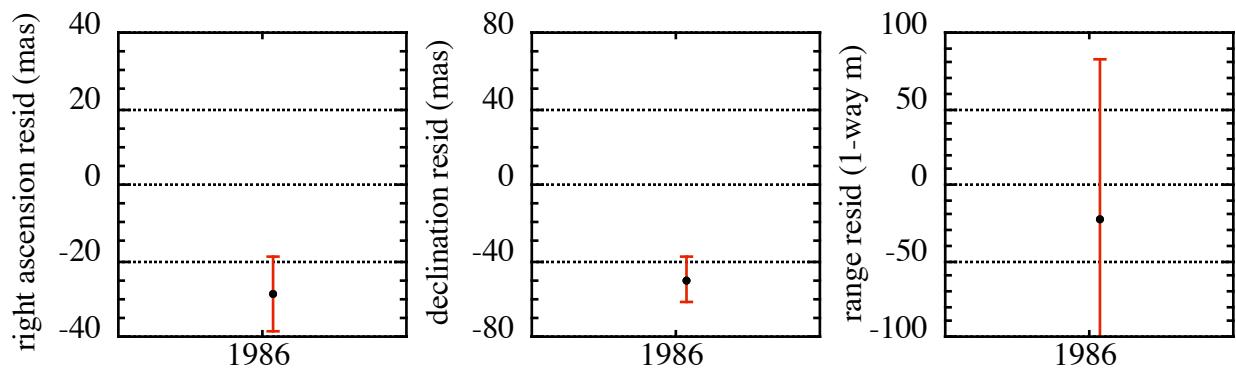


Figure B-27: Uranus right ascension, declination, and range from Voyager 2 encounter.

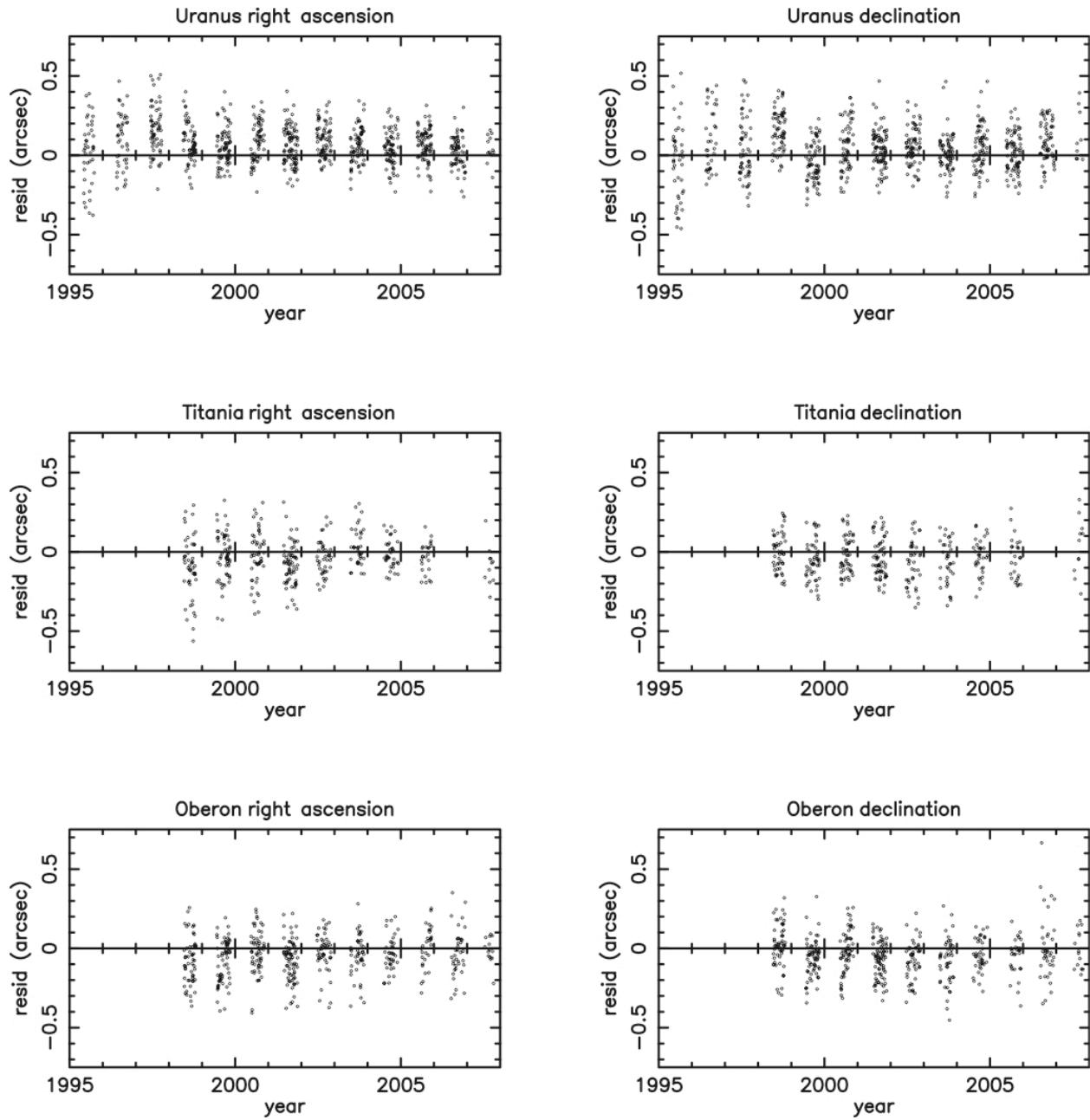


Figure B-28: Uranus observations from US Naval Observatory, Flagstaff.

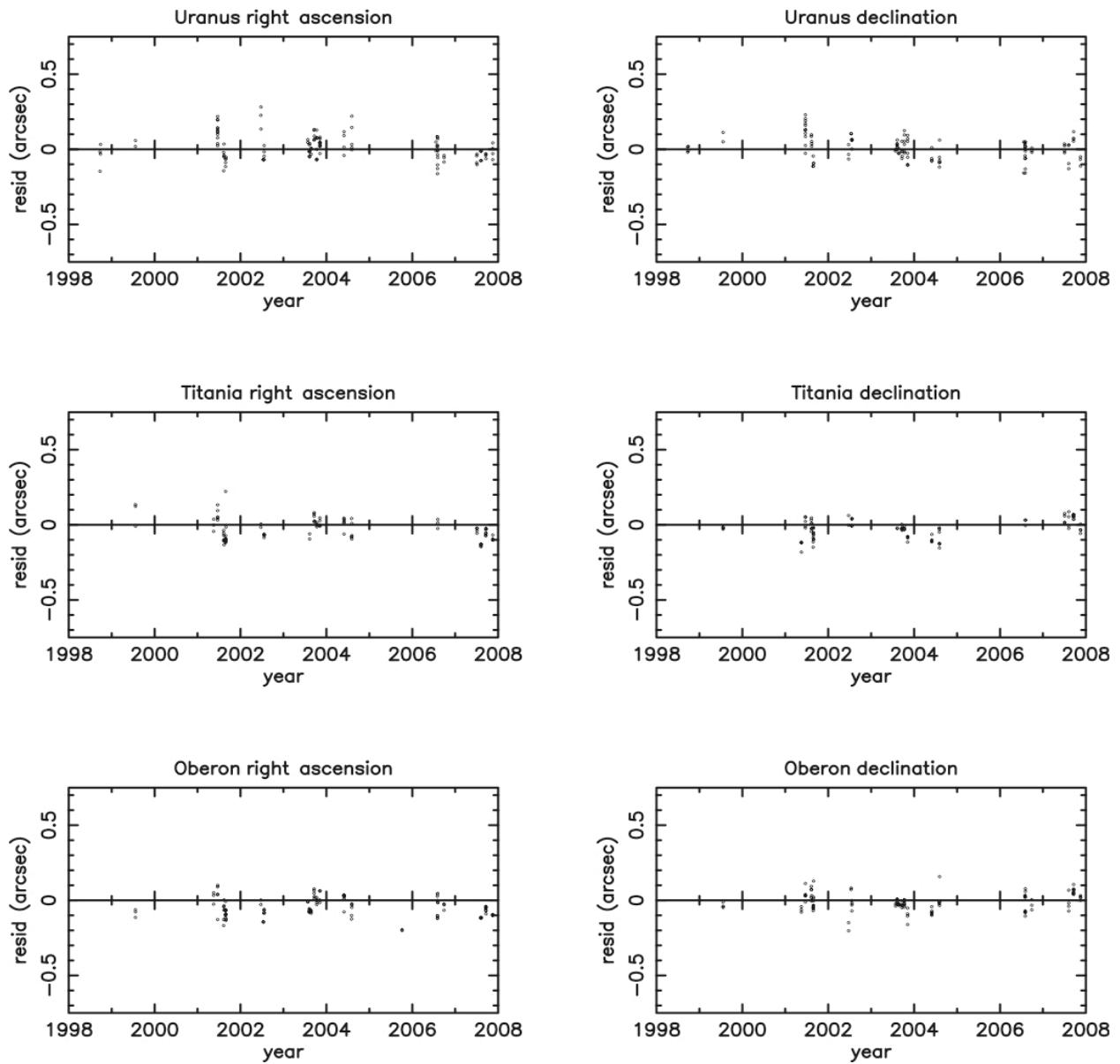


Figure B-29: Uranus observations from Table Mountain Observatory.

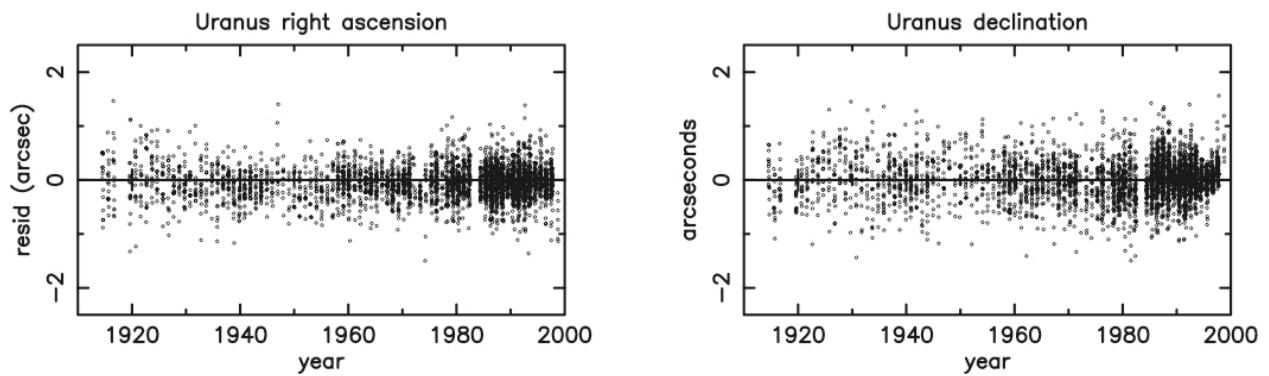


Figure B-30: Transit observations of Uranus

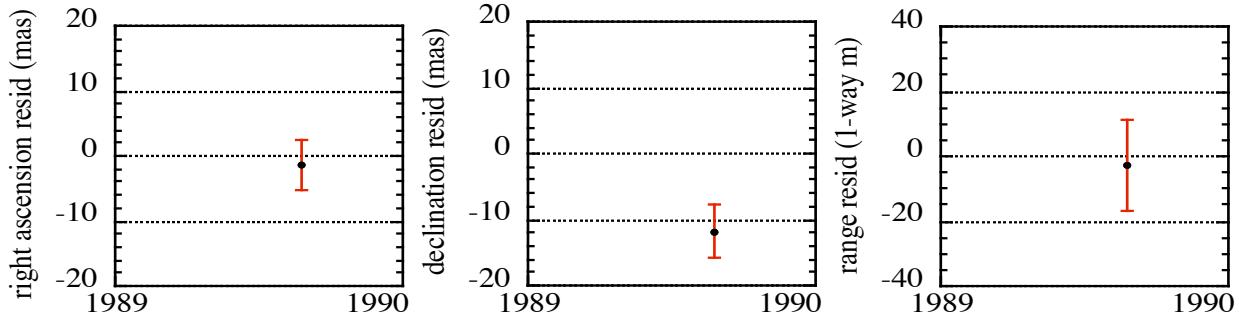


Figure B-31: Neptune right ascension, declination, and range from Voyager 2 encounter.

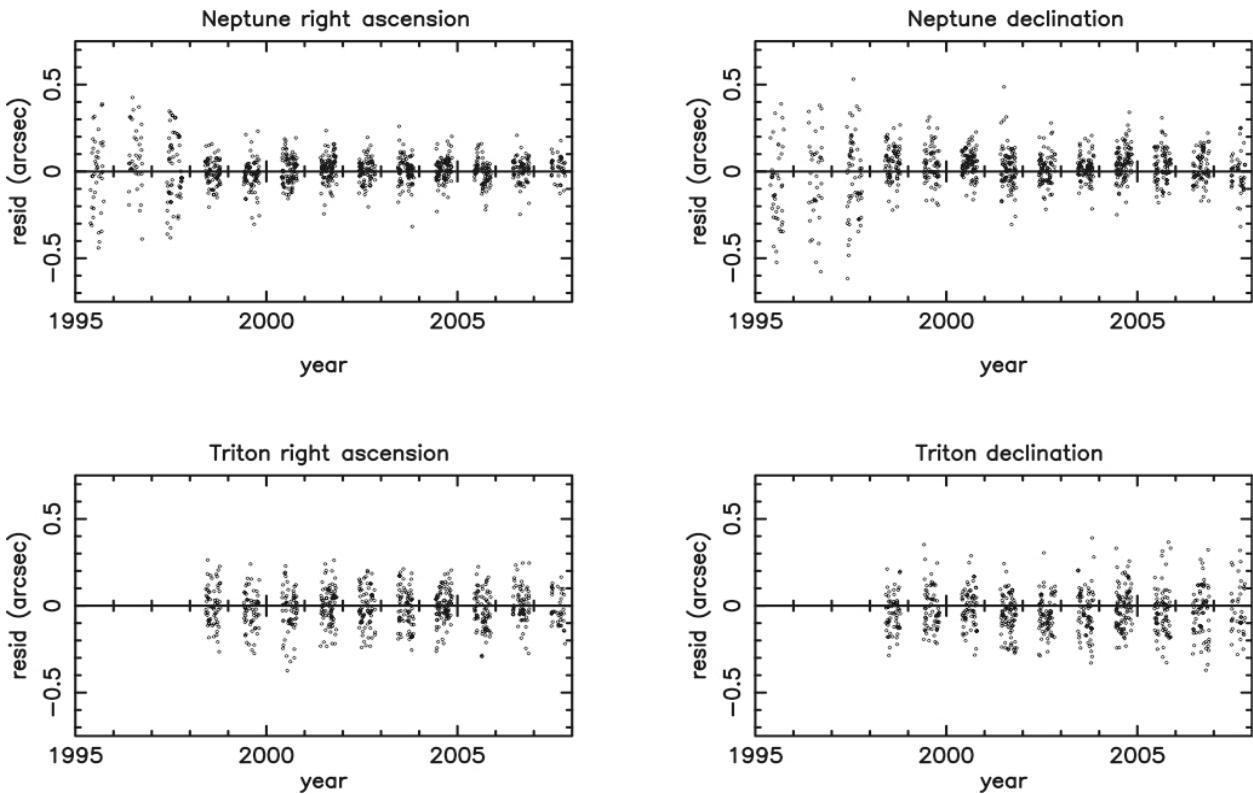


Figure B-32: Neptune observations from US Naval Observatory, Flagstaff.

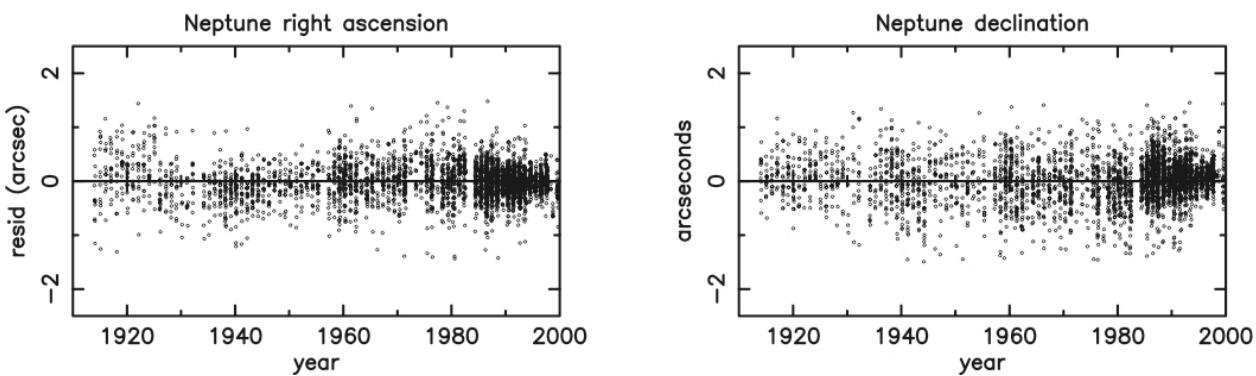


Figure B-33: Transit observations of Neptune

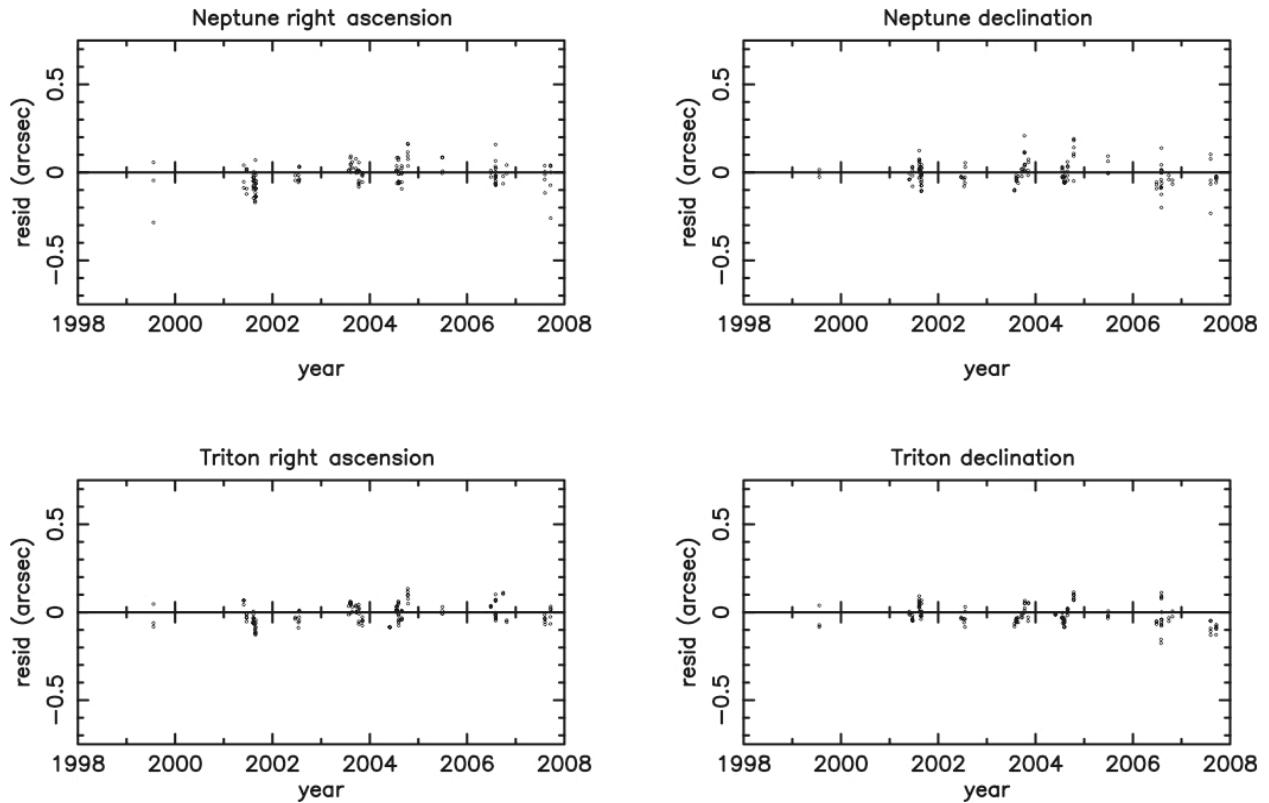


Figure B-34: Neptune observations from Table Mountain Observatory.

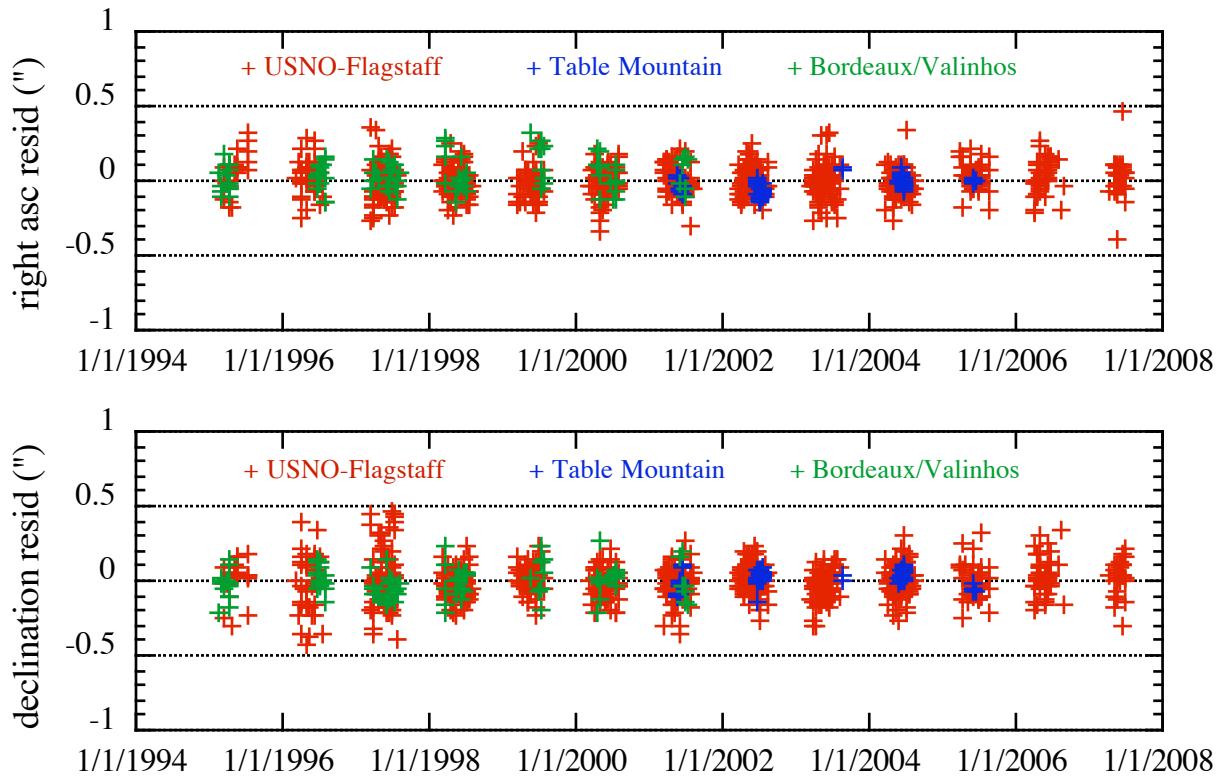


Figure B-35: Residuals of modern Pluto observations.

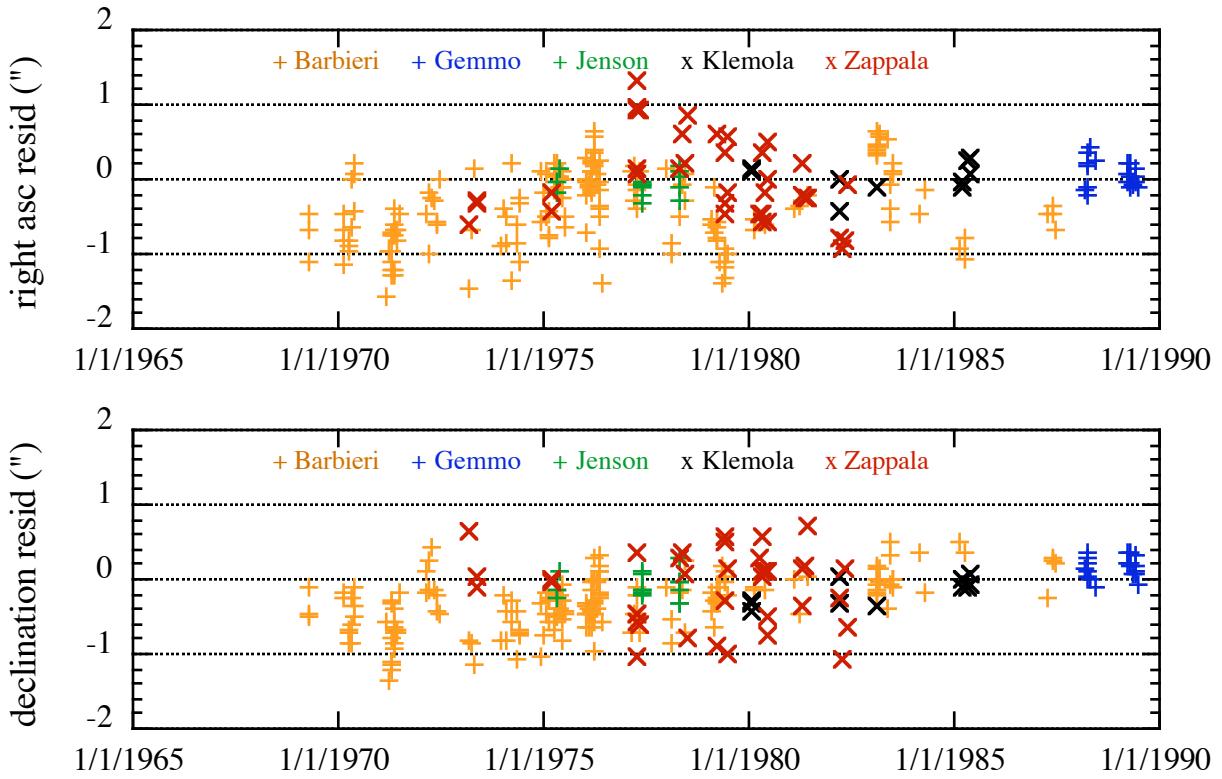


Figure B-36: Residuals of Pluto observations made 1968-1990.

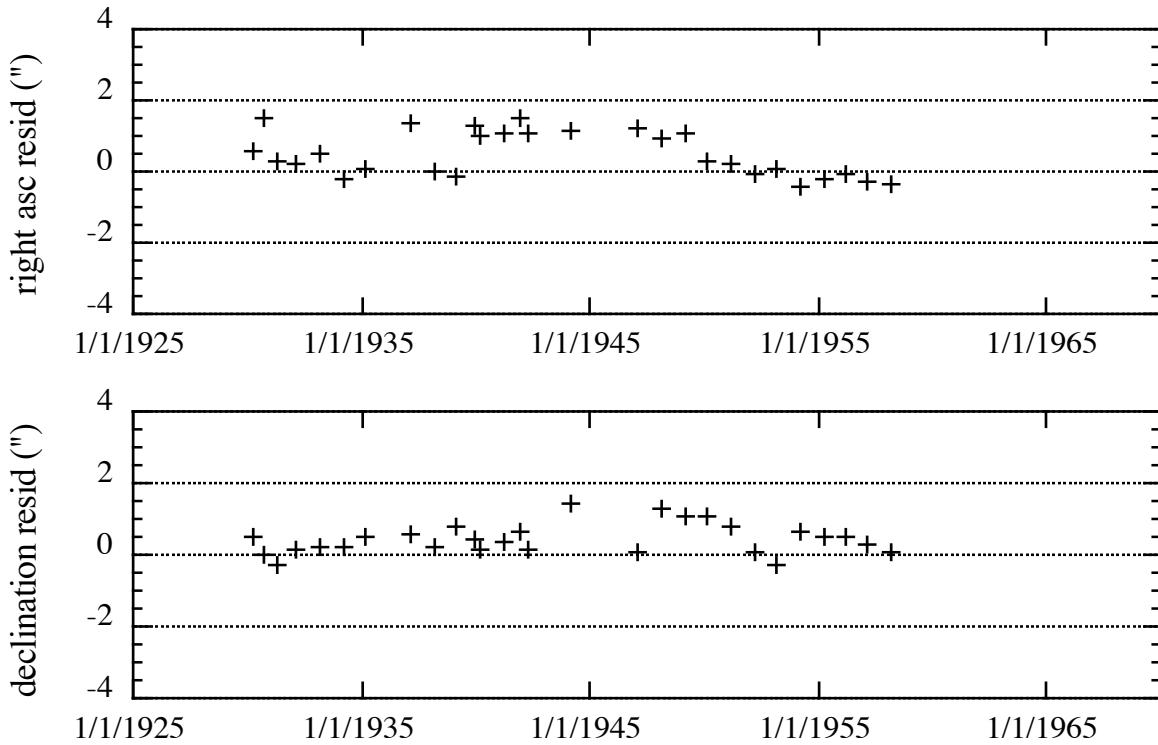


Figure B-37: Residuals of Pluto normalized points from Lowell, Yerkes, McDonald, etc.

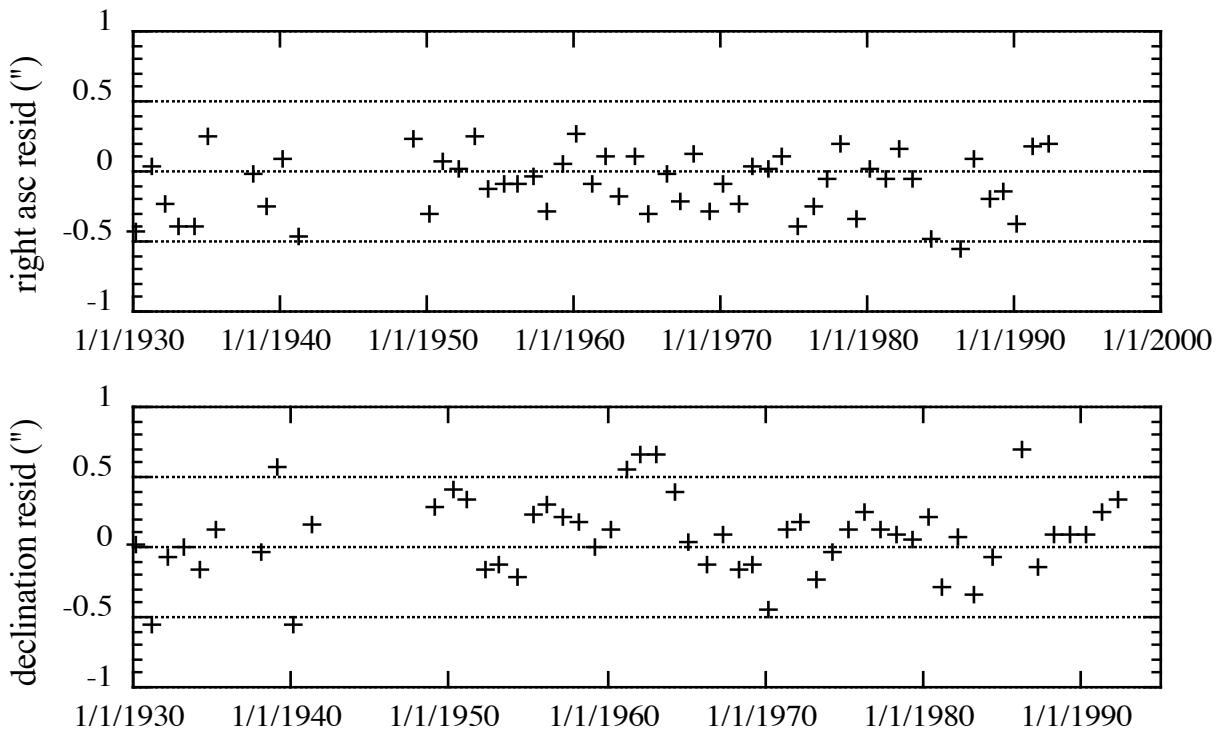


Figure B-38: Residuals of Pluto observations from Pulkovo astrograph.

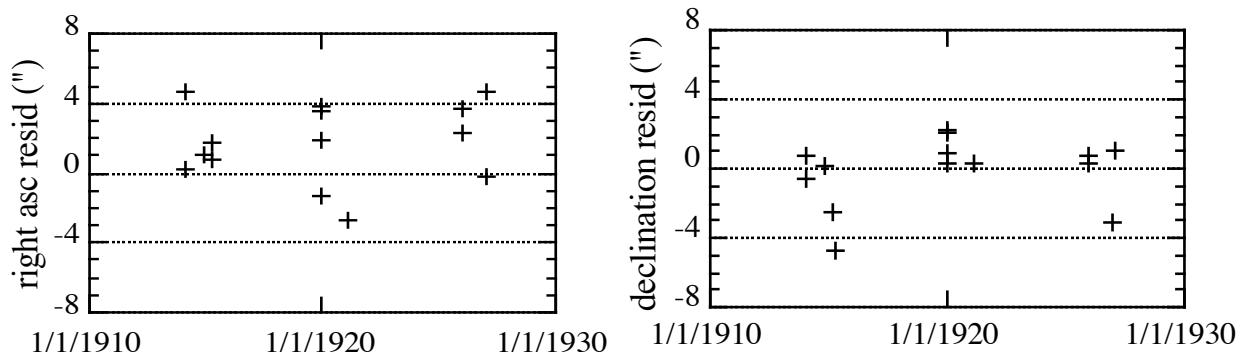


Figure B-39: Residuals of Pluto pre-discovery observations.

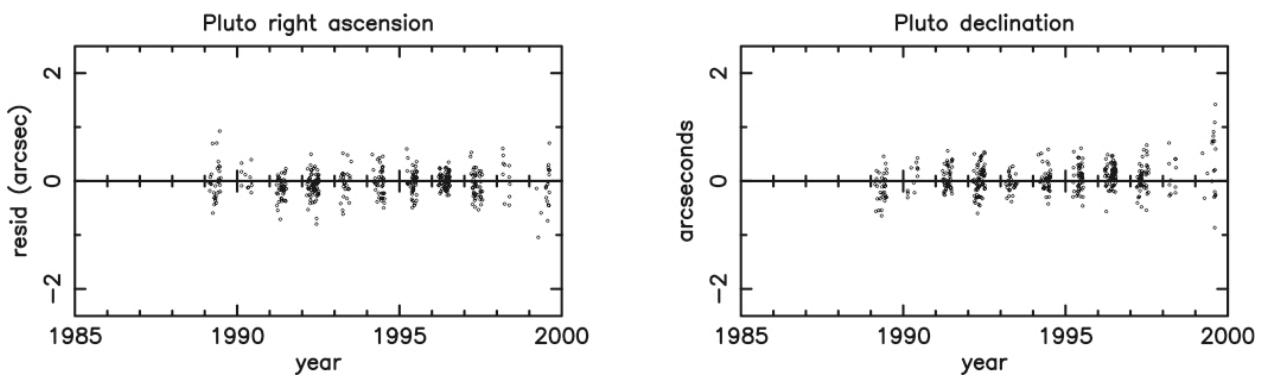


Figure B-40: Transit observations of Pluto